

# **Preliminary Seismic Risk Analysis Associated with Levee Failures in the Sacramento – San Joaquin Delta**

**Prepared for**

**California Bay-Delta Authority  
and  
California Department of Water Resources**

**Prepared by**

**Jack R. Benjamin & Associates, Inc.  
Menlo Park, California**

**In association with  
Resource Management Associates  
and Economic Insights**

**June 2005**

## **Executive Summary**

This report presents the results of a preliminary seismic risk analysis to estimate the effects of seismically initiated levee failures on Delta water quality and export and the economic consequences to the state. The purpose of this study is to conduct a preliminary analysis that provides an initial insight to the level of economic risk to the state and the risk-reduction opportunity (benefit) associated with undertaking a seismic upgrade of the levees on Sherman Island.

### **Background**

Jack R. Benjamin & Associates (JBA) was retained to scope and perform a Delta levees risk assessment for CALFED (now the California Bay-Delta Authority or CBDA) and the California Department of Water Resources (DWR). The work was to be performed in conjunction with a Levees Risk Assessment Team (LRAT) consisting of state and federal agency representatives and key expertise from the private sector. The assignment was to extend a previous study by CALFED's Seismic Vulnerability Sub-Team (CALFED, 2000). During the scoping phase (Phase 1), a work plan for conducting a seismic risk analysis (Phase 2) was developed, including a project schedule and a budget. In reviewing the work plan, it was apparent that available time and budget resources would not be adequate to perform the comprehensive seismic risk analysis envisioned for Phase 2. It was therefore decided to conduct a preliminary seismic risk analysis (constrained by available resources).

This preliminary analysis has two objectives:

- Obtain initial insights regarding the seismic risks for the Delta in its current condition, including a first, "ball-park" estimate of the water supply disruption and economic risk to the state associated with seismically initiated levee failures.
- Consider the risk-reduction opportunity (benefit) of upgrading the levees on Sherman Island, one of many options that exist for mitigating the risk.

Due to time and budget constraints, this initial evaluation relies on readily available information, extrapolations and engineering judgments. The analysis has "short-cut" many parts of the comprehensive risk analysis that is described in the work plan. In this context, the results of the present study provide valuable insight to the response of the Delta to a major seismic event and the impact that water supply disruptions would have on the state economy. These insights highlight the need to better understand Delta risks in order to support decision making on long-term policies and large capital expenditures associated with mitigating these risks.

### **Approach**

To estimate the seismic risk, a simplified approach was developed that takes advantage of available information, the results of previous studies, and the limited analyses that could be performed as part of this work. The elements of the analysis included:

- Risk of Levee Failure
- Seismic Scenario Evaluation
- Hydrodynamic Analysis
- Economic Analysis

**Risk of Levee Failure** – The seismic sub-team’s results (CALFED, 2000) were used to define the probability of occurrence of multiple, simultaneous levee failures due to earthquake ground shaking in the Delta.

**Seismic Scenario** — To evaluate the potential water quality and economic consequences of levee failures in the Delta, a single seismic event was chosen. The event was used to identify specific levee failures, estimate emergency response and levee repair, analyze hydrodynamic and water quality impacts, estimate the duration and amount of water export disruption, and assess the economic consequences to the state. The seismic event was chosen to be illustrative of major damage, so that consequences from such damage could be assessed. The seismic scenario involved 50 levee breaches for existing conditions in the Delta. Since 20 of these 50 breaches would have occurred on Sherman Island, the case with Sherman seismically upgraded had the 30 breaches from this same earthquake that were located on other islands.<sup>1</sup>

**Hydrodynamic Analysis** – Resource Management Associates (RMA), a subcontractor to JBA, conducted the hydrodynamics and water quality analysis; their report is provided in Appendix A. The RMA model was used to calculate Delta hydrodynamics and salinity for the defined scenarios. The earthquake was assumed to occur on July 1, 2002 and the historic Delta inflow data were used for the rest of water year. Then the historic data for water year 2002/2003 were used repeatedly until levee repairs were completed and water exports could return to normal. These hydrologic records were chosen to represent “normal” water years.

The earthquake and simultaneous occurrence of 50 or 30 levee breaches causes a substantial demand for and inrush of water into the islands with breaches and through the adjacent Delta channels. In the 50 breach scenario, 1.2 million acre feet of water rush into the Delta from Suisun and San Francisco Bays and flood 21 islands having an area of 94,300 acres. Water stage falls to –3 meters (10 feet below sea level) at the state and federal pumps, to –2 meters in Franks Tract, and to –1.5 meters in the Sacramento River and San Joaquin River as the nearby water in these channels rushes into the islands and creates a flow gradient from the Bay to the Delta. As the levees fail, water quickly flows in from the Bay to fill this void and the islands are flooded with each being substantially intruded by saline water. Salinity levels at the pump intakes escalate to three to fifteen times the criterion for acceptability. This assumes that pumping is suspended immediately when the earthquake occurs; salinity levels would become higher if pumping were allowed to continue.

**Economic Analysis** — To estimate the economic consequences to the state of levee failures and Delta water export disruptions, a group of economists was assembled under the leadership of Economic Insights. The economic analysis was conducted during a two-day workshop and relied on information provided by water agencies and expert judgment to estimate the economic costs and impacts<sup>2</sup> (including job years lost) associated with the 50-

---

<sup>1</sup> In a comprehensive risk analysis, the full range of earthquakes that could occur in or near the Delta and the complete set of scenarios involving combinations of levee failures on different islands would be evaluated.

<sup>2</sup> Economic costs are the net losses to the state, accounting for the direct, negative impacts as well as the positive effects (such as reduced operating expenses), whereas economic impacts are the gross or total consequences (i.e., reduction in the state’s gross output).

breach scenario (Delta As-Is) and the 30-breach scenario (Sherman Island Upgraded). The report of the economic work group is provided in Appendix B.

### **Assumptions/Approximations**

Major assumptions and approximations made in the analysis include:

- **Disruption Durations** – The water export disruption durations and associated water pumping restrictions that were estimated for the 50-breach (Sherman as is) and 30-breach (Sherman fixed) cases were interpolated back to zero breaches and extrapolated out to twice as many breaches.
- **In-Delta Economic Consequences** – The economics work group did not estimate the economic consequences that would occur in the Delta associated with levee repairs, damage to crops and other properties, emergency response management, etc. To estimate these consequences, cost information for the Jones Tract levee breach that occurred in June 2004 – which only involved one levee breach and flooding of two islands – was used to develop an in-Delta cost model.
- **Water Supply Export Disruption Economic Consequences** – We extrapolated the economic work group's estimated consequences for the given durations and amounts of water export disruption in order to estimate consequences for other durations/amounts.
- **Other Types of Water Years and Seasons for the Event** – The consequence information developed in this analysis was for a normal water year and for an earthquake that occurred on July 1. However, an earthquake can occur during any type of water year and at any time during the year. The earthquake probabilities and damages reported by the seismic sub-team do not consider water year types and event times. Thus, by combining our very focused and limited consequence information with information on all earthquakes, we are, in a sense, assuming that consequences in all water years and seasons will be, on average, similar to the ones we studied. This is unlikely to be the case. We know, for example, that an event occurring after a number of dry years will have significantly larger water supply disruption consequences (compared with the normal years considered in this analysis). For a wet period, consequences will be less, but it is not clear how much less. In addition, a fall or winter event will be better for some users (e.g., farmers, since they have already harvested and not yet planted), but worse for others (e.g., Contra Costa Water District, which tends to draw down its reservoir in the late summer and fall).

### **Results**

The analysis results are highlighted below.

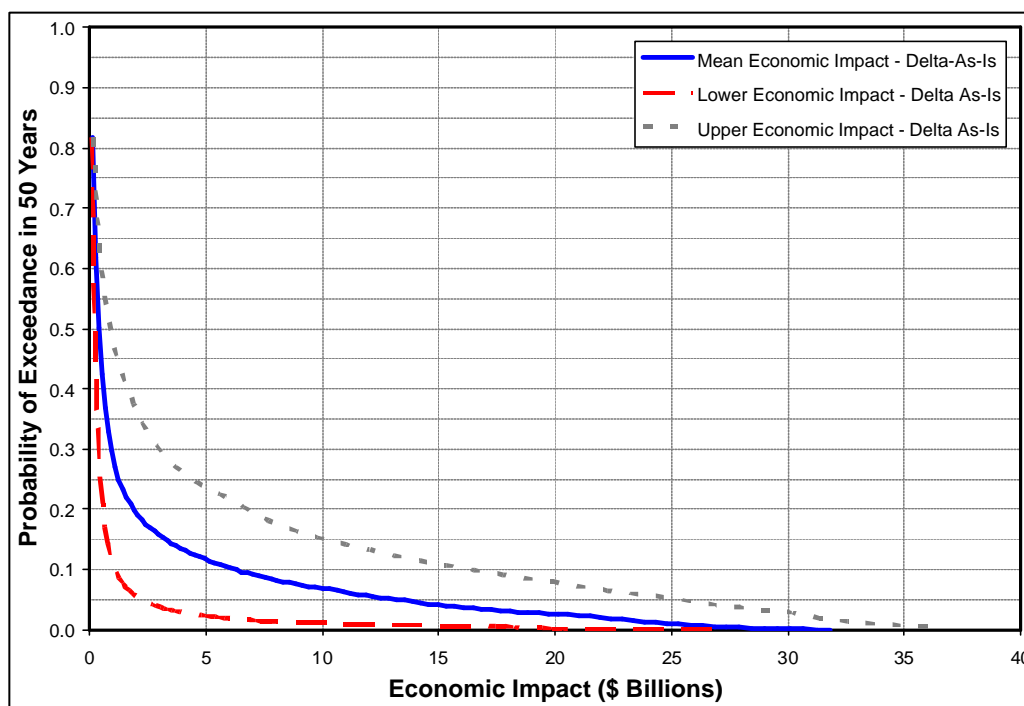
**Economic Consequences** - The economic evaluations for the seismic scenarios considered in the risk analysis provide insight into the magnitude of consequences that could occur as a result of a major seismic event. Two examples can be used for reference:

- **50 Breaches** -- The estimated economic impact to the state, including in-Delta and state-wide consequences for the 50 breach scenario is approximately \$10 billion. In addition, more than 10,000 jobs could be lost each year over a period of three years.

- 100 Breaches -- The economic consequence model projects potential losses for events up to 100 breaches – the maximum number of breaches considered by the seismic sub-team. For a 100 breach scenario, the economic impact to the state is approximately \$32 billion.

As discussed below, the assessment of economic consequences in this analysis are believed to be under-estimated. This is attributed in part to the approximations that were made and the limited scope of this preliminary analysis.

**Economic Risk** - Figure E-1 shows the estimated probability distribution of the economic impact to the state for a 50-year exposure period as a result of seismically initiated levee failures, for the Delta as it now exists. The lower and upper curves show the range of estimates based on the uncertainties in the estimated probability of levee failure (as assessed by the seismic sub-team) and the range in economic consequences as reported by the economic work group. The results suggest the state faces a significant economic risk (several \$10s of billions) if an earthquake causes a significant number of levee failures that lead to major water delivery disruptions. For example, Figure E-1 indicates in a 50-year exposure period there is a 10% chance the estimated mean economic impact of Delta levee failures and water delivery disruptions could exceed approximately \$6 billion. Considering the uncertainties that have been evaluated, the economic impact at this probability level may be as low as \$1 billion or as high as \$16 billion.



**Figure E-1 Probability distribution on the economic impact to the state as a result of seismically initiated levee failures in the Delta as it currently exists, assuming an exposure period of 50 years.**

**Potential Benefits of Upgrading Sherman Island** - By upgrading Sherman Island and effectively eliminating its contribution to the risk of levee failure and salt water intrusion into

the Delta, two benefits are realized. The first is the reduction in the number of levee failures and thus decreases in the volume of salt water intrusion, the area flooded and the number of breaches to be repaired. The second benefit is a reduction in the duration of water export disruption. Combined, these factors contribute to an expected economic risk-reduction benefit that is estimated to be about \$220 million. This suggests that economically appropriate public policy might allocate up to that amount for seismically upgrading Sherman Island or taking other effective actions to reduce (by a similar amount) the disruption of water delivery and the economic consequences of seismically induced levee failures.

### **Observations**

The results of this preliminary seismic risk analysis provide a first quantitative look at the consequences to the state in terms of water delivery disruption and economic impacts. Although preliminary, the results show the state to be at considerable risk in the event an earthquake leads to levee failures, with subsequent intrusion of salt water into the Delta and disruption of water export. The risk-reduction benefit of seismically upgrading Sherman Island levees was considered as one option to mitigate the impact of levee failures. This evaluation suggests that mitigation strategies (such as an upgrade to Sherman Island) that can reduce the duration of water delivery disruption are fiscally supportable in terms of their economic risk-reduction benefit.

Observations from this analysis highlighted the complexity of evaluating the risk to the Delta from seismic events and the impact levee failures have on water quality and the economy. These include:

- Delta hydrodynamics and thus water quality can vary considerably depending on the details of a seismic scenario; e.g., number and location of levee breaches and number of islands flooded.
- For a given scenario (number and location of levee breaches and flooded islands and associated Delta inflows), the sequence of levee repairs can significantly impact water quality and export disruptions.
- The estimate of economic consequences likely under-estimates the consequences that may be experienced by the state due to the preliminary nature of this analysis. Limited resources and scope required simplifications that skipped over some sectors and consequences and resulted in de facto estimates of zero – thus introducing an inherent bias toward under estimation.
- For a given scenario, it is expected that water quality, export disruption, and economic consequences to the state will vary significantly depending on the timing of an earthquake in a year and the recent, current, repair-period and post-repair hydrology (i.e., wet, normal or dry years).
  - For example, reservoirs (especially south of the Delta) are operated on an annual cycle. If the earthquake occurs when they are at low storage levels, more severe consequences are expected.
  - Similarly, reservoir storage may be low if the year(s) or months preceding the earthquake are dry or critically dry, and this would mean that the water projects had less water to allocate for the disruption period.

- Dry or critically dry water years during the repair period could result in a more severe disruption because of less water for flushing and less water to export when limited pumping becomes possible.
- At the end of the repair period, south of Delta storage is likely to be critically low. Occurrence of a dry or critically dry year under that circumstance would continue the adverse consequences of the event for a substantial time.
- Wet years are expected to reduce adverse impacts, but less markedly than dry years increase them.

The work plan prepared in Phase 1 calls for a comprehensive risk analysis that will address the factors such as those highlighted above, that substantially affect water quality, export disruption, and economic risks.

## Contents

Executive Summary .....	i
1. Introduction .....	1
1.1 Background.....	1
1.2 Purpose .....	1
1.3 Analysis Scope .....	2
1.4 Project Participants .....	2
1.5 Report Organization .....	2
2. Approach.....	4
2.1 Analysis Steps.....	4
2.2 Elements of the Risk Analysis.....	4
2.3 Approximate Approach.....	5
2.4 Assumptions.....	8
3. Seismic Evaluation Case.....	11
3.1 Seismic Event.....	11
3.2 Levee Failures.....	13
3.3 Breach Size.....	14
3.4 Emergency Response and Repair.....	14
3.5 Timing and Water Conditions.....	17
3.6 Other Factors .....	17
4. Evaluation of Water Quality and Delivery Disruption .....	19
4.1 Water Quality Assessment .....	19
4.2 Export Disruption.....	20
5. Economic Consequences .....	22
5.1 Approach .....	22
5.2 In-Delta Consequences.....	23
5.3 Water Supply Consequences .....	26
5.4 Overall Economic Consequences from Seismically Initiated Levee Failures.....	29
6. Risk Quantification and Risk-Reduction Analysis .....	32
6.1 Delta As-Is Seismic Risk Results .....	32
6.2 Seismic Risk Results for Sherman Island Upgraded .....	32
6.3 Risk-Reduction Assessment.....	35
7. Observations .....	40
8. References.....	42

**Appendix A – Delta Levees Seismic Risk Assessment Modeling 30 and 50 Breach Scenarios**

**Appendix B – Economic Consequences of Water Supply Disruption Due to Seismically Initiated Levee Breaches in the Delta**



## **1. Introduction**

### **1.1 Background**

This report presents the results of a preliminary seismic risk analysis to estimate Delta water quality and export disruption and the economic consequences to the state as a result of seismically initiated levee failures. The genesis of this analysis and the context within which the results should be viewed are summarized.

This study was conducted as part of a project that had two phases. Phase 1 involved the development of a detailed work plan for conducting a seismic risk analysis for the Delta. The risk analysis was to assess the impact of levee failures on water quality and export. As defined in the project scope, the work plan was to be developed in conjunction with a levee risk assessment team (LRAT) which was comprised of a multi-disciplinary group of technical experts, including representatives from the California Bay-Delta Authority (CBDA), California Department of Water Resources (DWR), U.S. Army Corps of Engineers, and other Delta stakeholders. As part of the work plan development, the LRAT met three times.

Phase 2 of the project called for implementation of the work plan.

The project was briefly interrupted in early 2004, a fallout of the state's fiscal crisis. Following restart of the project in summer of 2004, DWR requested the scope of work be expanded to include assessment of economic consequences to the state that would result from earthquake initiated levee failures and Delta water export disruptions.

During work plan development, discussions with the LRAT about the scope of the seismic risk analysis indicated there was little information available on Delta levee failures and their impact on water quality. As a result, CBDA and DWR were asked to approve activities to gather information and carry out limited computations that would expand our knowledge base. They agreed with the need for this work, which supplemented the development of the work plan, and approved work to be carried out in two areas. The first involved gathering information with respect to material and equipment available for repairing levee breaches and the time required for breach repair. The second area involved performing a series of hydrodynamic calculations to evaluate the response of the Delta to alternative levee breach scenarios and the impact on water quality. In both areas, the results provided valuable information that helped guide development of the work plan.

As the work plan was being finalized, it became clear the current project schedule and budget would not support the effort to implement the work plan (i.e., conduct the full-scope seismic risk analysis). As an alternative, DWR requested that a scope of work be outlined for an initial seismic risk analysis to be performed within the available schedule and budget. This report is the product of this limited effort. The following subsections describe the purpose and scope of this effort.

### **1.2 Purpose**

The purpose of this study is to conduct a preliminary seismic risk analysis that assesses (1) the seismic risk that Delta levees pose for the state and federal water projects and the state's economy and (2) the risk-reduction opportunity (benefit) associated with undertaking a major seismic strengthening of the levees on Sherman Island. The choice to focus on

Sherman Island, one of many potential mitigating actions that could offer risk reductions, is motivated by a couple of factors. These include:

- the state of California owns the majority of the island, thus offering considerable flexibility for implementation of any upgrades,
- the results of the CALFED seismic sub-team analysis (CALFED, 2000) indicated the levees on Sherman Island are weaker, and therefore have a greater likelihood of failure due to earthquake ground motion than levees on other islands, and
- initial hydrodynamic calculations identified the importance of levee failures on Sherman Island to water quality and the disruption of Delta water exports.

For these reasons, seismically strengthening Sherman Island seemed to offer significant opportunity for risk reduction with respect to reducing the likelihood and severity of water quality and delivery disruptions.

Notwithstanding the above, a seismic upgrade of Sherman Island was not compared with other risk-reduction opportunities that exist.

### **1.3 Analysis Scope**

The overall scope of this preliminary analysis is to initially assess the seismic risk to Delta water exports and examine the risk-reduction benefit of seismically-upgrading Sherman Island. The risk reduction-benefit was evaluated in terms of the reduction in the likelihood and magnitude of the seismically related economic consequences to California that would be realized if the Sherman Island levees were upgraded. To do this, the analysis considered two cases:

1. Delta as-is, and
2. Sherman Island upgraded to a level that levee failure and island flooding does not occur or has a sufficiently low probability of occurrence that it makes effectively no contribution to the seismic risk.

The scope of the seismic risk evaluation was dictated by the remaining time and resources available.

### **1.4 Project Participants**

An analysis of the seismic risk associated with levee failures in the Delta and subsequent water export disruptions and economic consequences is a multi-disciplinary assessment. It involves seismic hazards and fragility analysis, risk analysis, hydrodynamic and water quality modeling, economic analysis, marine-based construction associated with levee repair, etc. The participants in this study and the areas of expertise are listed in Table 1-1.

In addition to the individuals identified in Table 1-1, the study team utilized the experience gained during the development of the Delta seismic risk work plan. In particular, the observations and input of the LRAT and some of the data and tools that were developed during that effort were helpful (see the discussion in Section 1.1).

### **1.5 Report Organization**

Section 2 describes the approach taken to conduct this preliminary analysis, including the analysis steps and inputs, assumptions, and limitations.

**Table 1- 1 List of Project Participants**

<b>Participant</b>	<b>Discipline</b>
Martin W. McCann, Jr.	Risk analysis, seismic engineering
Will Betchart	Water resources, risk analysis
John DeGeorge	Hydrodynamic Modeling
Stacie Grinbergs	Hydrodynamic Modeling
Wendy Illingworth	Economic analysis
Steve Hatchett	Economic analysis
Ray Hoagland	Economic analysis
Roger Mann	Economic analysis
Rick Rhoads	Marine Construction

Note the earlier work by the CALFED Seismic Vulnerability Sub-Team was a crucial input to this project.

Section 3 defines the seismic scenario that is evaluated, including the timing of the event, hydrologic conditions, etc.

In Section 4 the results of the hydrodynamic water quality analysis for the cases evaluated are summarized.

Section 5 describes the approach taken to evaluate the economic consequences of Delta water supply disruption and the results of the analysis.

In Section 6 the elements of the analysis are combined to obtain an initial estimate of the Delta seismic risk (“Delta As-Is”) and the risk-reduction benefit that may be achieved if the Sherman Island levees are seismically upgraded.

Finally, Section 7 provides a series of observations based on this initial analysis.

References are provided in Section 8.

Appendices provide documentation of the hydrodynamic and water quality calculations performed (Appendix A) and the results of the economic consequence analysis (Appendix B).

## **2. Approach**

As described in the Delta seismic risk analysis work plan, an analysis of the economic risk to the state is a significant, multi-disciplinary undertaking. It requires assessment of the water quality and delivery impacts and the subsequent economic consequences associated with the full range of possible earthquakes (of varying size and location) and levee breach scenarios, the variation in hydrologic conditions and reservoir storage, time of year, etc. Considering the complete suite of events involving seismic levee failures, the economic risk to California can be estimated. In the present analysis, a less comprehensive (more approximate) approach is taken.

As discussed in Section 1, there are two elements in the scope of this analysis. The first is to conduct an initial assessment of the economic risk to the state associated with seismically initiated levee failures in the Delta. The second part of the analysis considers the risk-reduction benefit of seismically upgrading Sherman Island. Implied in an evaluation of the benefits associated with upgrading Sherman Island is an accounting of all the benefits and costs that may be realized from such a project. The present analysis is limited in its scope — so such a full accounting of all benefits (i.e., reduced risk of island flooding, potential increases in income, reduced levee maintenance costs, etc.) and costs (i.e., design and construction costs, lost revenues from leases, etc.) is not considered. The analysis is limited to considering the risk-reduction benefit that would be realized by a reduction in the likelihood and magnitude of economic consequences due to seismically initiated levee failures if Sherman Island were seismically upgraded. Other economic benefits are not evaluated.

### **2.1 Analysis Steps**

The following steps were performed to evaluate the risk-reduction benefit of upgrading Sherman Island:

1. Evaluate the economic risk to the state that is a consequence of seismically initiated levee failures in the Delta for current conditions. This analysis includes an estimate of the probability of levee failures, the impact of levee failures on water quality and the disruption of exports, and the economic consequences of delivery disruptions.
2. Evaluate the economic risk to the state assuming Sherman Island has been upgraded to an extent that seismic levee failures and resultant island flooding do not contribute to the likelihood or severity of water export disruptions and economic risks to the state.
3. Assess the risk-reduction benefit of upgrading Sherman Island.

The following subsections describe the seismic risk analysis approach, the assessment of risk-reduction benefits, and analysis assumptions.

### **2.2 Elements of the Risk Analysis**

To estimate the seismic risk, a simplified approach was developed that takes advantage of available information, the results of previous studies, and the limited analyses that could be performed as part of this work. The elements of the analysis are:

- Risk of Levee Failure

- Seismic Scenario Evaluation
- Hydrodynamic Analysis
- Economic Analysis.

**Risk of Levee Failure** - The CALFED seismic sub-team (CALFED, 2000) estimated the probability of occurrence of levee failures due to earthquake ground shaking in the Delta. This distribution is shown in Figure 2-1 for exposure periods of 1 and 50 years. As part of the sub-team's analysis, the uncertainty in the frequency of earthquake occurrences and in the number of levee breaks was estimated and included in their estimate of the annual probability of the number of levee breaks. In Figure 2-1 this uncertainty is shown by the 15<sup>th</sup> and 85<sup>th</sup> fractile curves.

**Seismic Scenario Evaluation** – To evaluate the potential water quality and economic consequences of levee failures in the Delta, a seismic event was defined. This event was used to identify specific levee failures throughout the Delta, estimate emergency response and levee repair timing and costs, analyze hydrodynamic and water quality impacts, estimate the duration and amount of water export disruption, and assess economic consequences.

**Hydrodynamic Analysis** - Hydrodynamic and water quality calculations were performed to model the intrusion of salinity into the Delta and to estimate the disruption to water export for the seismic scenario.

**Economic Analysis** – The economic consequences to the state were evaluated, including the costs of emergency response and levee repair, in-Delta impacts associated with island flooding and damage to Delta facilities (i.e., pipelines, roads, etc.), and the impact of water supply shortages to urban and agricultural customers, etc. To estimate the economic risk to California from seismic levee breaks and resultant island flooding, an economic work group evaluated the consequences associated with the estimated water delivery disruptions. The results of the economic work group were used to develop a relationship that estimates the economic consequences as a function of the number of levee breaks. This transformation is schematically displayed in Figure 2-2<sup>3</sup>.

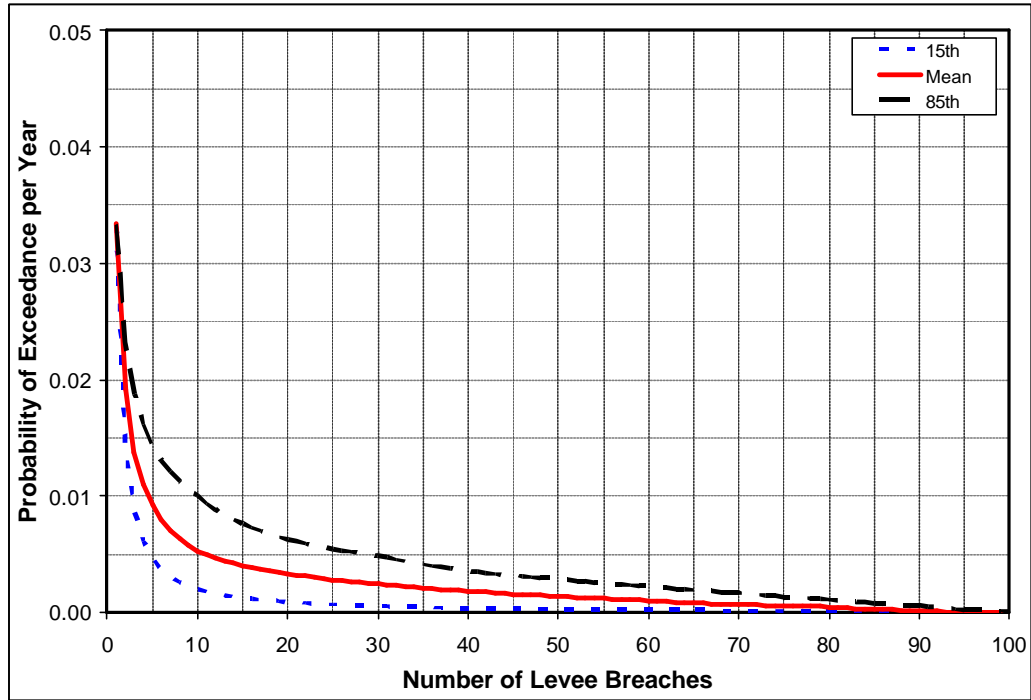
### 2.3 Approximate Approach

To obtain a relationship between the number of levee breaks and the economic consequences to the state, a simplified, risk model was developed. The approach was motivated by the available probabilistic information on levee failures (see Fig. 2-1) and the opportunity to approximate the economic consequence distribution shown in Figure 2-2 based on limited hydrodynamic and water quality modeling experience gained during the work plan development and calculations performed as part of this study, the recent Upper Jones Tract levee failure in June 2004 (DWR, 2004) and limited economic consequence evaluations that could be performed as part of this study.

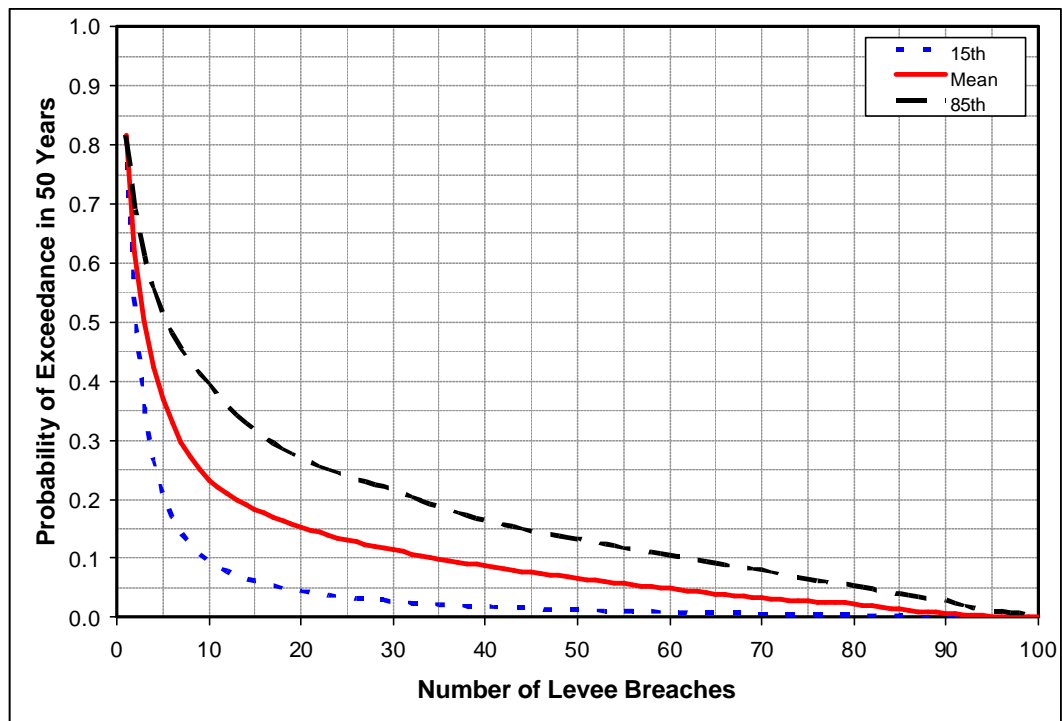
The following general observations are relevant to estimating the probability and magnitude of economic consequences associated with levee breaks in the Delta:

---

<sup>3</sup> The discussion here (of a relationship between the number of levee breaks and the economic consequences to the state) simplifies the complexities in developing such a relationship. These complexities would be explicitly considered in a comprehensive risk analysis as described in the work plan.



(a)



(b)

**Figure 2- 1 Probability distribution on the number of seismically initiated simultaneous levee breaches in the Delta for exposure periods of a) one, and b) fifty years (scaled from Fig. 5-2, CALFED (2000)).**

- When a relatively small number of levee breaks occur (less than 10), the economic consequences will likely be mainly from the direct costs for emergency response and repair (including pumping out flooded islands), and certain in-Delta impacts (i.e., damage to other infrastructure, agriculture, property damage). Water supply deliveries are unlikely to be disrupted for an extended period of time (especially in normal water years) and, as a result, there will be limited state-wide economic consequences due to disruption of the state and federal water projects.
- The Upper Jones Tract levee break in 2004 provides cost data for levee repair and short-term in-Delta impacts. This information can be used to estimate the direct costs of levee breaks and island flooding.
- The probability distribution on the number of levee breaks provides insight to the overall probability level of the economic risk distribution.

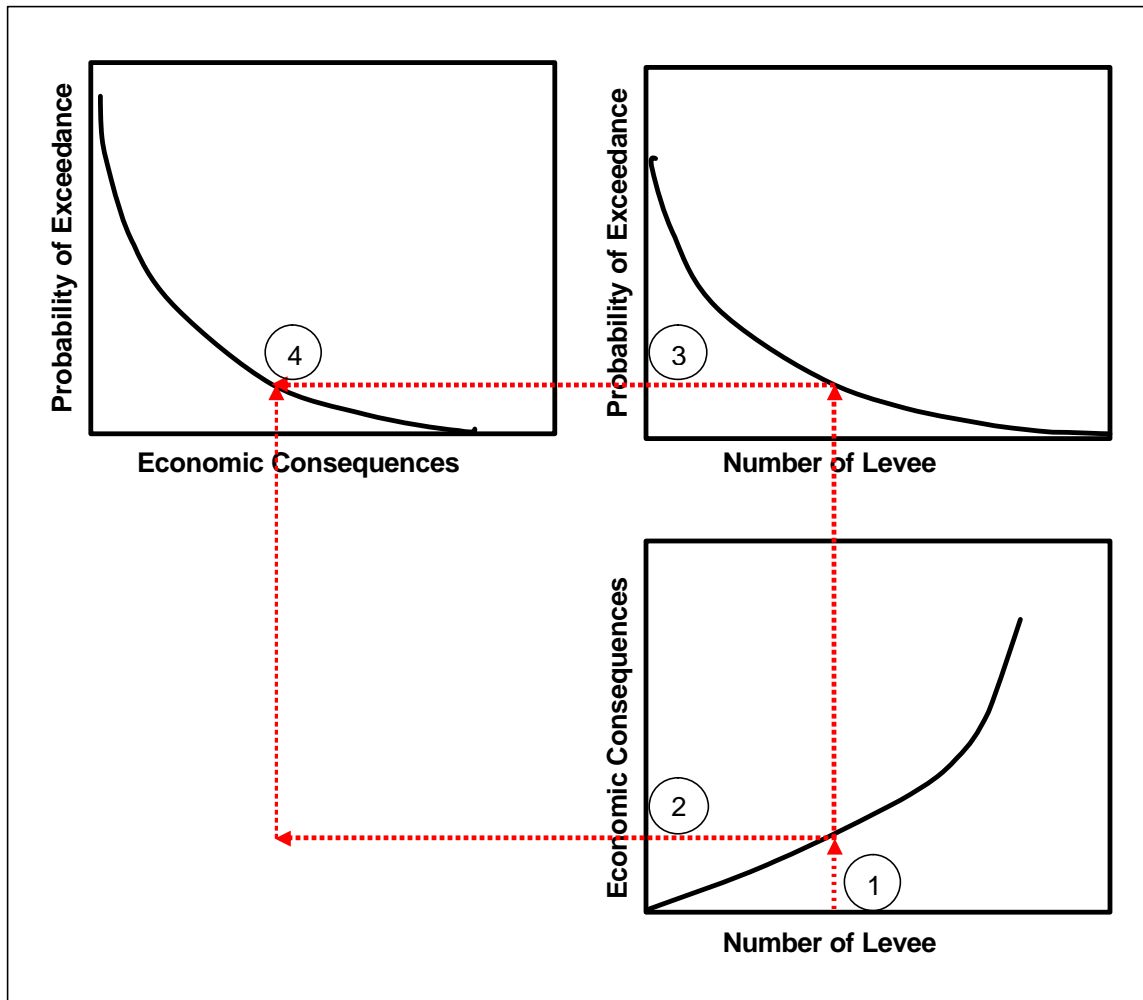
What is missing from the above description is the needed understanding of the level of economic consequences associated with levee breaks that result in extended water delivery disruptions.

Recognizing beforehand that available resources for this analysis would permit only two hydrodynamic calculations to be performed (one for the Delta as-is and the other for the case with Sherman Island upgraded) and a similar number of economic consequence analyses, this work focused on obtaining an estimate of the economic consequences on a part of the risk distribution where the economic costs would involve both the repair costs and immediate in-Delta consequences and the impacts to the overall state economy due to water export disruption.

To estimate the economic consequences as a function of the number of levee breaks the following approach was taken:

1. Develop a model to estimate the in-Delta consequences (i.e., emergency response and repair costs, etc.) based on the data available from the Upper Jones Tract levee failure in 2004.
2. Based on point-estimates of the economic consequences (costs and impacts) to the state for the seismic scenarios evaluated, develop an estimate of the consequences as a function the number of levee breaks, accounting for the number of islands flooded and the duration of water delivery disruptions.

To implement this approach an estimate of the economic consequences must be made for a range of levee breaches. Based on results of hydrodynamic calculations for 3 and 10 levee breaches, it is apparent that water delivery disruptions would likely be in the range of 3 to 6 months. A disruption of this duration would not be likely to result in substantial water supply shortages and economic impacts during normal water years.



**Figure 2- 2 Schematic illustration of the derivation of the distribution on economic risk due to levee breaks.**

To estimate the economic consequences associated with extended water delivery disruptions, it was judged that a scenario involving more than 20 levee failures must be considered. For purposes of this analysis, an assessment based on 50 levee breaks is considered. Coupled with this analysis will be an assessment (assuming Sherman Island is upgraded), that excludes the breaches on Sherman Island.

## 2.4 Assumptions

The following summarizes assumptions in this analysis. The assumptions have been grouped into general categories:

### Seismic and Other Damages

1. Any earthquake damage that might occur to other facilities or infrastructure was assumed to have no impact on levee repair operations in terms of availability of material, equipment, manpower, funding or scheduling of repairs.



2. It was assumed that no other water system failures occur that might cause additional disruption or which would result in a significant loss of existing water storage. If other damage were to occur, it was assumed that repairs could be made quickly so they do not constrain Delta export opportunities that may occur during the wet season. In particular, the Mokelumne and Hetch Hetchy aqueducts were assumed to be unaffected.
3. For levee seismic damage that does not result in a full breach, it was assumed that repair would occur with other resources, e.g., with rock from other quarries. Such damage would not divert breach repair resources or extend the breach repair schedule, even if the damage escalated into a full breach.
4. For levee damage that may occur after the earthquake (say as the result of wind and wave action on the interior slopes of the levees of a flooded island), it was assumed that stabilization and repair would occur with other resources, e.g., rock from other quarries. Such damage would not divert breach repair resources or extend the breach repair schedule, even if the damage escalated into a full breach.

### **Breach Geometry**

1. All breaches were assumed to be of “typical” geometry and varying widths (from 500 to 1,600 feet), established by the times at which their levee ends were capped with rock to prevent additional breach growth. In particular, it was assumed that no “long breaches” would occur where several thousand feet of levee collapse to a below sea level crest elevation.

### **Emergency Response and Repair**

1. It was assumed that export pumps would be shut down immediately upon occurrence of the earthquake and that they would not be restarted until water of acceptable quality (800 umhos/cm EC or 500 mg/l total dissolved solids) could be drawn to the pumps from the central Delta (e.g., Franks Tract).
2. It was assumed that all breaches would be repaired and that breach repair would be the critical path item for resumption of undisrupted water export.
3. The limiting factor for the rate of progress on breach repair was assumed to be production of suitably graded rock for delivery by barge to the breach sites. The San Rafael Quarry was assumed to be the source of this material because of its advantageous location for loading to barges.
4. The quarry was assumed to be fully dedicated to supplying rock for breach closure and operating curfews were assumed waived. Thus, with a 24-hour, 7-day per week operation, the quarry’s maximum production rate of 15,000 tons per day was the key limitation for rate of progress. Marine equipment (barge cranes, barges, and tugs) was assumed to be mobilized from other regions as needed to deliver and place rock at the above rate.
5. It was assumed that rock from other quarries would not be available to supplement this production because it would be needed for other customers (e.g., San Rafael Quarry customers forced to go elsewhere) and for other repairs, such as described in Nos. 3 and 4 under “Seismic and Other Damage” above.
6. It was assumed that each island would be pumped out at a rate of 500 cfs (+/-) as soon as the final breach repair on that island occurred. The salinity of discharged water was considered in the water quality analysis.

7. It was assumed that the most southerly breaches (near the state and federal pumps and on the channels that feed them) would be repaired first and the repair sequence would progress northward. This assumption was based on analysis results for a different closure sequence (south last) that was found to be ineffective.

### **Hydrologic Data**

The Delta hydrologic data from June 1, 2002 through September 30, 2003 were used (assuming a July 1, 2002 earthquake) and the October 1, 2002 through September 30, 2003 portion of this record was repeated for subsequent water years until the end of the disruption period. This was selected because it was seen as a “normal” hydrologic period from the viewpoint of Delta hydrodynamics and water quality. Note that the July 1, 2003 south of Delta water storage was seen as more “normal” from a water supply economics viewpoint, so July 1, 2003 water storage data were used resulting in an assumed July 1, 2003 earthquake date for estimation of economic consequences.

### **Flushing**

It was assumed that all water that would have been exported (pumped) if the earthquake had not occurred was used for flushing salinity out of the Delta. The historical daily flows for pumping were simply redirected to “Net Delta Outflow.”

### **Partial Pumping**

When the southern levee breaches had been closed, the islands pumped out, and the northern and central Delta flushed to an extent that would allow fresh water to be drawn to the pumps, partial pumping was assumed to commence, even though flooded islands and unclosed breaches still existed in the central and northern Delta. It was assumed that additional Delta outflow would be required to counteract the additional tidal prism and mixing caused by remaining breaches, so pumping would be restricted to one-third the historical amount for summer and two-thirds the historical amount for winter. Note, this is a professional “best estimate” judgment of the restricted pumping amount based on the hydrodynamics/water-quality experts’ familiarity with the Delta and the results of a simulation using a different (south last) breach repair sequence.

### **Economic Consequence Modeling**

1. The Mokelumne aqueduct, Hetch Hetchy aqueduct, and in-district facilities (Los Vaqueros reservoir and local distribution pipelines) were assumed to avoid major damage.
2. Friant Dam was not re-operated to meet the needs of the Mendota Pool exchange contractors.
3. Water in SWP terminal reservoirs was included in the project allocation, rather than being allocated only among those agencies who have paid for the terminal reservoirs.
4. Operation restrictions at San Luis Reservoir (maximum drawdown rates, San Felipe low point) did not restrict water deliveries.

### 3. Seismic Evaluation Case

This section sets forth the parameters used to define the seismic scenario for which the economic consequences are estimated. The scenario is defined by the following elements:

- Earthquake event
- Estimated number of levee breaches, and identification of levee breach locations
- Estimate of levee breach dimensions
- Emergency response and repair
- Time of year
- Hydrologic conditions
- Reservoir storage at the time of the earthquake

The following subsections describe each element of the seismic scenario.

Given the definition of the scenario to be evaluated, hydrodynamic calculations were performed to evaluate the water quality and export disruption impact. This part of the analysis is described In Section 4.

#### 3.1 Seismic Event

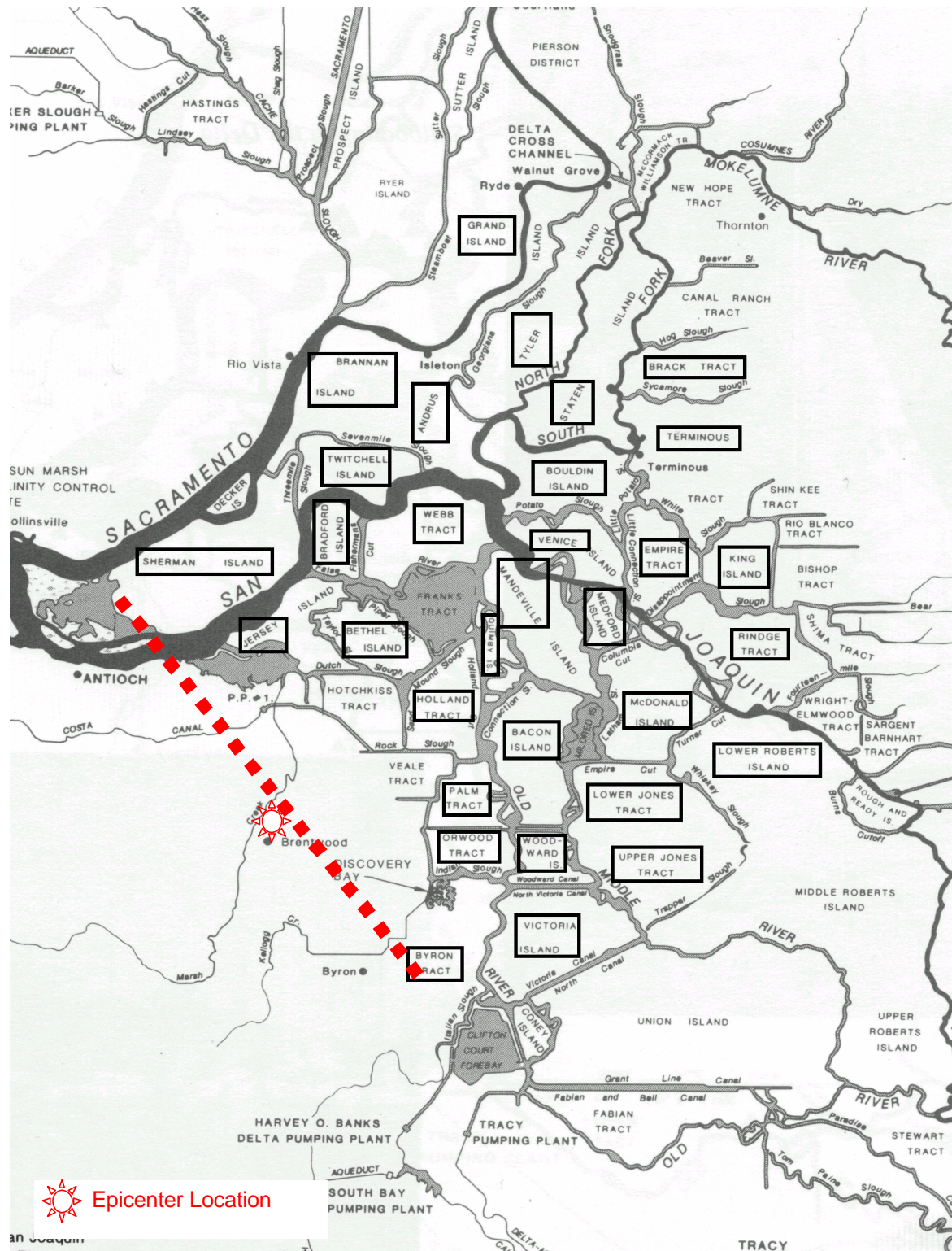
As described in Section 2, the assessment of water quality and deliver impacts and economic consequences will be made for an event involving 50 levee breaks. This event has a mean annual probability of exceedance of  $1.4 \times 10^{-3}$ . More meaningfully, it has a mean probability of exceedance in a 50-year exposure period of 0.06 (i.e., 6%). To identify the possible location of these breaches, a seismic event was defined and the ground motion for this event estimated. For purposes of this analysis, the earthquake was used as one event that is representative of a suite of earthquakes of varying magnitude and location that could occur (CALFED, 2000) in or near the Delta that could produce ground motions leading to a large number of levee breaches.

For purposes of this analysis, it is reasonable to assume the relative likelihood for a large number of breaches to occur is highest for earthquakes of moderate to large magnitude (greater than 6.0) and which are located in or near the Delta.

The earthquake is based on the seismic hazard analysis in the CALFED seismic sub-team report (CALFED, 2000). The seismic sub-team modeled the seismic sources (faults) in the Delta region and the magnitude and rate of earthquake occurrences that could occur in each source. For the present analysis, the following event was defined:

- Earthquake Magnitude: 6.5 (moment magnitude scale)
- Seismic Source: Coast Range – Central Valley Boundary Thrust Fault
- Epicentral Location: One kilometer north of Brentwood

Figure 3-1 shows the location of this earthquake, including the estimated fault rupture.



**Figure 3- 1 Map showing the epicentral location and rupture length of the seismic scenario event.**

Based on the CALFED (2000) report, the scenario earthquake is on the Coast Range – Central Valley (CRCV) seismic source, which is a thrust fault zone located along the western edge of the Central Valley for most of the Valley's length. It has been recognized only relatively recently because the fault traces are buried with relatively little surface evidence. Attention was drawn to this fault system by the Coalinga earthquake ( $M_W$  6.5) in 1983. In retrospect, the system has been identified as the possible source of approximately eleven significant earthquakes along the west side of the Central Valley during the past 140 years ( $M_W$  5.8 to 6.8), including three in the Vacaville-Winters area in 1892 (the maximum being  $M_W$  6.8) and one in the Antioch area in 1889 ( $M_W$  6.3) (Wakabayashi and Smith, 1994).

There is not uniform acceptance of the CRCV as the source model for these earthquakes, especially in the immediate vicinity of the Delta. The CALFED seismic sub-team recognized this by basing its analysis on two, alternative Delta-area source models (one was the CRCV) and by weighting the two models equally (CALFED, 2000).

The length of the fault rupture for this event was calculated using the relationship of Wells and Coppersmith (1994, their Table 2A). The calculated length (25 kilometers for  $M_W$  6.5) is consistent with the segment length of (41 km) and the maximum magnitude ( $M_W$  6.8) indicated by the CALFED seismic sub-team.

The distribution of ground motions in the Delta for the scenario earthquake was estimated using the peak ground acceleration (PGA) attenuation relationship developed by Abrahamson and Silva (1997). This is one of the models used in the CALFED (2000) seismic hazard analysis. To estimate the potential distribution of levee breaches, contours of PGA were plotted on a detailed map of the Delta so that the length of levees falling within 0.05g peak acceleration intervals on each island could be measured. These lengths were tabulated and combined with levee fragility information (discussed in the next sub-section) to estimate the distribution of levee breaches on each island.

### **3.2 Levee Failures**

The CALFED seismic sub-team assessment of fragility was applied, as detailed in Table B-7 (CALFED, 2000). This fragility assessment was developed by the sub-team for each of four Damage Potential Zones and expressed as an estimated range of the normalized number of failures expected per hundred miles of levee at any given peak ground acceleration. Two modes of failure were addressed (liquefaction and inertial failures) and the results were then summed by the sub-team to estimate the range for the total rate of failures (per 100 miles of levee) for a given level of peak ground acceleration. The approach included allowance for the effects of the Delta's soil column (soft soil site amplification). Table B-7 was developed for a  $M_W$  6.0 earthquake, and the sub-team provided scaling factors in their Figure B-4 to adjust estimates for each failure mode in order to consider events of smaller or larger magnitude.

For each damage potential zone and failure mode, the appropriate magnitude-scaling factor was used to estimate the  $M_W$  6.5 normalized range of failure rates per 100 miles of levee, for each peak acceleration addressed by the sub-team. The  $M_W$  6.5 earthquake may generate ground accelerations that exceed the 0.3 g maximum for which the sub-team provided failure rate estimates. To address this, a linear extrapolation of the sub-team's failure rate increase between 0.2 and 0.3 g was assumed. This is believed to be a reasonable assumption for the purpose of the present analysis. Although it does provide higher estimates of the numbers of failures as peak accelerations increase, it does not appear to overestimate the increase. The resulting total failure rate (per hundred miles) was then

multiplied by the appropriate number of miles in each acceleration interval on each island to estimate the range in number of failures for that island. Based on the range calculated for each acceleration interval, a specific number of failures was chosen and were located on the island's levees, based on judgment. When an acceleration zone was indicated to have levee failures, breaches were located in that zone, generally giving preference to locations closer to the rupture trace. The resulting breach locations are presented in Figure 3-2.

### **3.3 Breach Size**

Several factors influence breach size. The depth of the breach will usually be at least to the bottom of the peat layer, thus deep peat deposits will usually mean a larger (deeper) breach. If an island has only one breach (as compared with multiple breaches) all the water for flooding the island flows through, scours, and increases the size of the single breach. Thus, single breaches will usually be larger. Also, breach size will be influenced by the length of time it takes to get the levee ends capped. Breaches that wait for a couple months to get the levee ends capped will have eroded into larger breaches than would have been the case if they had been capped within a couple weeks.

To respond to these factors, each breach was given a rating for size (A for small through C for large) based on the depth of peat at the breach location and whether there were other breaches on the island. Then, based on a capping schedule, the breach size rating was increased one level if capping was to take more than 14 days and another level if capping was to take more than 35 days. Thus, a C breach could grow into a D or an E breach.

Each category was then assigned a breach length and closure material requirement, based on assumption of a standard cross-section geometry as developed earlier in this project by Moffatt and Nichol. The breach lengths and volumes of closure materials used were:

A. 500 feet	115,000 tons
B. 700 feet	160,000 tons
C. 1,000 feet	225,000 tons
D. 1,300 feet	290,000 tons
E. 1,600 feet	355,000 tons

### **3.4 Emergency Response and Repair**

After a short mobilization and ramp-up period, the limiting factor in the levee repair schedule was the supply of rock for levee end capping and breach closure. The assumptions in defining this rate of production were the following:

- Capping and breach closure material would come from Dutra's San Rafael quarry because of its unique advantage (in northern California) of direct access to marine transportation.
- Rock would not be imported by ship (import from Canada has been identified as a potential, but was not factored into this scenario due to technical/logistical details that may impede or prevent this as an option).



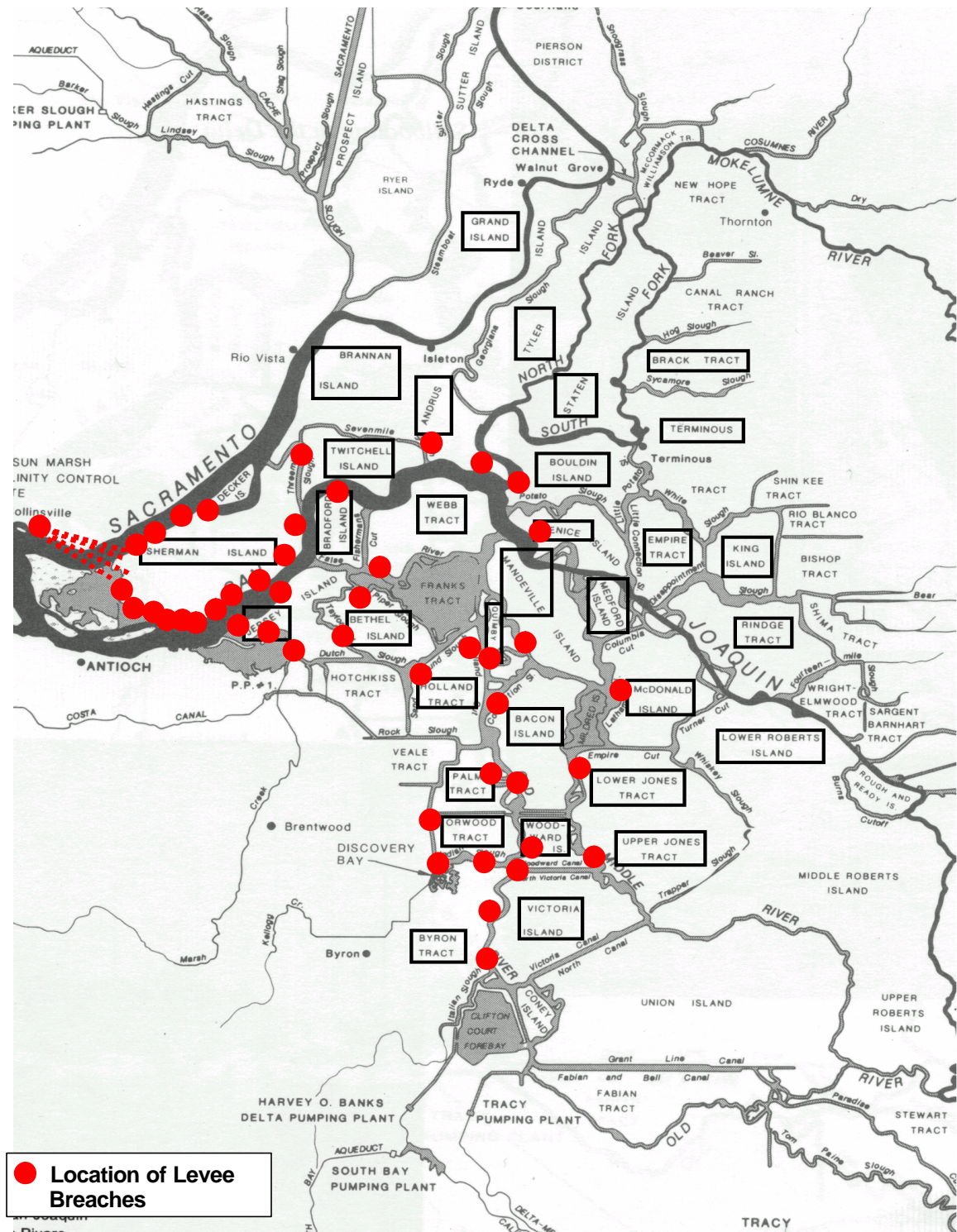


Figure 3- 2 Location of the 50 levee breaks.

- Rock potentially available from other quarries in the region without direct marine access would be required for other purposes (see below).
- Other Delta needs for rock (e.g., to repair non-breach levee damage or to armor the interior slopes of levees on flooded islands) would be addressed by other regional quarries and would not divert rock or marine equipment from breach closure.
- The San Rafael quarry's other customers would be served by other sources, allowing full dedication of quarry capacity to levee breach closure.
- The San Rafael quarry's curfew requirements would be waived, allowing 24-hour, 7-day operation.
- The capacity of the San Rafael quarry is 15,000 tons per day.
- Total rock remaining in the San Rafael quarry is indicated to be 30 million tons. The amount required by this incident has been estimated to be less than half that amount, thus the total quarry resource should be adequate.

The above assumptions are derived from discussions with the CALFED Levee Risk Assessment Team during the fall of 2003 and from analytical work performed by Moffatt and Nichol earlier in this project.

Marine equipment (barge cranes, tug boats and rock barges) is estimated to be available as needed and not to constrain the closure schedule. This requires a maximum of ten barge cranes during levee end capping operations and six operating barge cranes during the entire levee closure period. Also, sufficient barge and tug capacity would be required to deliver the full production of the quarry to the rock placement equipment. It is anticipated that such equipment would need to be mobilized from outside the Bay Area.

The above assumptions translate into a 28 month repair period for the 50 breach scenario and a 16 month repair period for the 30 breach (Sherman Island levees upgraded) scenario.

The schedule sequence for breach closure was initially established based on the experience of the water quality modelers as derived from earlier simulations of various one breach cases, a three breach case, and a ten breach case. The judgment was that central Delta islands would cause the greatest pumping disruption due to salinity intrusion and tidal mixing and, thus, they should have their breaches closed first. Then Sherman Island would be closed and, finally, the south Delta islands would be closed. As discussed below, the water quality modeling indicated that this closure sequence was an error. The south Delta islands appear to have extreme importance as trappers of salt (from the first gulp of intruded water when the earthquake and breaches occur). That salt is then available and the tidal movements mix it with any fresh water that is being conveyed toward the pumps as long as the south Delta breaches are still open. This contamination is sufficient in the scenarios examined to make the water too salty to pump. Thus, the major conclusion of the water quality modeling was that closing the south Delta breaches first appears to be the more desirable sequence and should provide the opportunity for partial (restricted) pumping when all the southern breaches have been closed but additional breach repairs still are needed in the central Delta.



### **3.5 Timing and Water Conditions**

The earthquake was assumed to occur on July 1. Water conditions were chosen to be “normal” in order to assess typical consequences. For hydrodynamics in the Delta, July 1, 2002, the remainder of water year 2001/2002, and water year 2002/2003 were judged to be normal. South-of-Delta storage on July 1, 2002 was judged to be somewhat low. Therefore, July 1, 2003 south-of-Delta storage (which was more normal) and only water year 2002/2003 were used to evaluate economic consequences.

### **3.6 Other Factors**

In addition to the above factors that define the seismic scenario and its impact on the Delta, the following conditions or assumptions were used:

- Other damage that might be expected to occur as a result of the earthquake was assumed to have no impact on levee repair operations, in terms of the availability of material, equipment, manpower, funding, scheduling of repairs, etc.
- It was assumed no other water system failures occur that might cause additional disruption or which would result in a significant loss of existing water storage. If other damage were to occur, it is assumed that repairs could be made quickly so they do not constrain Delta export opportunities that may occur during the wet seasons. In particular, the Mokelumne and Hetch Hetchy aqueducts are assumed to be unaffected.
- No additional levee failures are considered that might result from wave action on the interior levee slopes of flooded islands.
- No additional levee breaches are considered that might result from levees that may have been damaged (but not breached) in the earthquake and whose condition could deteriorate and result in a breach (say due to wind-wave action).

**Table 3- 1 Summary of the Seismic Scenario**

Feature/Parameter	Properties	
Scenario Seismic Event	Earthquake Magnitude: Epicentral Location: Earthquake Ground Motions in the Delta (Range):	6.5 (moment magnitude) 1km northwest of Brentwood 0.0 – >0.70g Peak Ground Accelerations
Delta Breaches	21 Islands Flooded  50 Breaches Bacon – 2 Bethel – 2 Bouldin - 1 Bradford – 1 Brannon/Andrus - 2 Byron – 1 Holland - 2 Jersey – 4 Lower Jones - 1 Mandeville – 1 McDonald – 1 Orwood - 2 Palm - 2 Quimby - 1 Sherman Island – 20 Twitchell – 1 Upper Jones - 1 Venice – 1 Victoria - 1 Webb – 1 Woodward – 2	
Repair Period	Delta As-Is: 28 months Sherman Island Seismically Upgraded: 16 months	
Duration of Water Delivery Disruption	Delta As-Is: 28 months Sherman Island Seismically Upgraded: 16 months	
Event Date	July 1	
Water Year Type	Similar to 2003	

## **4. Evaluation of Water Quality and Delivery Disruption**

### **4.1 Water Quality Assessment**

The RMA model was used to calculate Delta hydrodynamics and salinity for the 30 and 50 breach seismic scenarios. The earthquake date was assumed to occur on July 1, 2002 and the historic Delta inflow data were used for the rest of water year 2001/2002. The historic data for water year 2002/2003 were used repeatedly until the repair was completed and water export could return to normal. These hydrologic records were chosen to represent “normal” water years.

The earthquake and simultaneous occurrence of 50 or 30 levee breaches causes a substantial demand for and inrush of water into the islands with breaches and through the adjacent Delta channels. In the 50 breach scenario, 1.2 million acre-feet of water rush into the Delta from Suisun and San Francisco Bays and flood 21 islands having an area of 94,300 acres. Water stage falls to –3 meters (10 feet below sea level) at the state and federal pumps, to –2 meters in Franks Tract, and to –1.5 meters in the Sacramento River and San Joaquin River as the nearby water in these channels rushes into the islands and creates a flow gradient from the Bay toward the Delta. Water quickly flows in from the Bay to fill this void and the islands are flooded with each being substantially intruded by saline water. Salinity levels at the pump intakes escalate to three to fifteen times the criterion for acceptability. This assumes that pumping is suspended immediately when the earthquake occurs; salinity levels would be higher if pumping were allowed to continue.

As a result of the levee breaches and island flooding, there is a significant decrease in the tidal range (the difference in water elevation for high tide versus low tide). The normal tidal range of one to 1.5 meters at the pumps is reduced to about 0.25 meters. In Franks Tract, the normal range of one to 1.5 meters is reduced to about 0.5 meters. Even in the Sacramento River, the normal range of one to 1.5 meters is reduced to 0.75 to one meter. This is because of the much larger volume of water subject to tidal influence and the limited capacity of flow constrictions (such as the levee breaches, Delta channels and the Carquinez Strait). The impact of this reduction in tidal range is for intruded salt to be trapped for a longer time than would otherwise be the case. For example, if the tidal range at the levee breach for an island is only one foot rather than three feet, only about one third as much water flows out of an island and back in during a tidal cycle. Thus, if fresher water is available in the channel to dilute the island salinity, many more tidal cycles will be required to accomplish the dilution. The salinity, especially in the southern Delta, is therefore seen to persist.

It was necessary to establish specific operating assumptions for the water projects during the incident. Immediately stopping the pumps was one such assumption, but a relatively obvious one. The pumping facilities may sustain some damage and thus some period of shut down would likely be required for inspections and repairs even without water quality concerns. Another operating decision was needed to establish what would be done with the water flowing into the Delta in the historical record, but not being pumped in this scenario. Would it be saved in the upstream (Sacramento Valley) reservoirs or would it be allowed to continue flowing into the Delta to provide some flushing benefit? This is not a straightforward decision. Space in upstream reservoirs is limited and specific amounts of space must be empty as the wet season approaches in order to provide for flood control. Still, if a “save the water” approach were implemented, about 2 million acre-feet of water could have been kept in upstream reservoirs going into the first wet season. Since water

managers would not know whether the coming winter would be wet or dry or something in-between, they might argue for saving the water to be safe and have more to pump next year. However, if the wet season were not dry, the reservoirs would then be nearly full (except for flood control space) and essentially all the wet season water would need to be released. This would make winter flows in the Delta a little higher, but that water might have been more effective for flushing the Delta if it had been used earlier. RMA was able to try both approaches. Because of the persistent salinity, it was found that using (as flushing water) all the water not pumped was more effective than saving it temporarily and using it as a larger flushing flow at the beginning of the wet season. Because of the importance of salinity persistence, the historical Delta inflows were used in the scenarios and water not pumped was used as flushing water whenever available. It remains for future simulations to show whether there is an effective strategy for saving some of the water that would have been pumped as insurance against a dry winter.

Another factor that was important is the salinity contributed to the Delta channels during island pump out. This is due to the relatively high volume of water that must be discharged and the slow rate of exchange/dilution, especially in the southern Delta. Pump out (with its residual salinity) appears to prevent achieving the required salinity criterion until all the southern breaches are repaired, the islands are pumped out and a flushing period has occurred.

The sequence of breach closure appeared to be the single most important factor for water quality modeling. The initially adopted sequence had been developed based on prior seismic breach scenario calculations involving 3 and 10 breaches and the modelers' judgment as to which islands would be most important in affecting Delta salinity levels. This led to an assumption that the western and central Delta would receive early repair scheduling. In retrospect, it appears that the southern islands should have received the early priority because the intruded salinity takes so much longer to be flushed from the southern locations. There was neither time nor budget in the present effort to perform model runs for the change in repair sequence.

#### **4.2 Export Disruption**

Using the above scenarios, and the criterion that salinity must be 500 mg/l or less (Ec of approximately 800 umhos/cm or less) to be pumped, water quality was calculated by RMA with no pumping until the required salinity level was achieved and judged to be sustainable with pumping. The analysis indicated the wet season flows, during the first winter after the earthquake, were not adequate to flush the south Delta enough to allow pumping. In fact, it was clear that water quality would not improve sufficiently until all the south Delta levee breaches were closed and this source of salinity was removed. Since the south Delta breaches were scheduled to be closed last, this meant no export pumping for the whole repair periods. It was therefore clear that the breach closure schedule that was originally assumed was not optimal; it resulted in a worst case scenario for export pumping and in hindsight would not be adopted if the incident were to actually occur. Therefore it could not be used as a basis for further analysis of incident consequences.

A revised schedule for breach closure was developed that gave priority to closing south Delta breaches first, then working northward toward the central Delta and working on Sherman last. Using the revised repair schedule, it was estimated that the 50 breach repairs would progress enough to allow partial export pumping 11.5 months after the earthquake. The 30 breach scenario would progress to a similar repair status 10.5 months after the earthquake (because of less capping time and slightly smaller breach sizes). This

revised breach repair schedule, for which we were not able to run a separate hydrodynamic and water quality simulation, was used to estimate the consequences of the incident on export pumping – on the basis of professional judgment. These estimates were then forwarded to the economic work group.

The rate of partial pumping was estimated based on expected requirements for additional carriage water due to the central Delta islands with breaches that had not yet been closed. Full pumping was then expected to resume when the final breach in each scenario was closed. Cumulative amounts of pumping were calculated for the intervals established in Table 4-1 for input to the economic consequences analysis. It was assumed that no more water would be available from upstream reservoirs than that indicated as Delta inflow in the historical flow data for the hydrologic period being used. To the extent that extra water was needed for flushing or carriage water, that amount of water would not be available for pumping. The undisrupted (no earthquake) amounts of pumping are shown in the table for comparison.

**Table 4- 1 Estimated Delta Export Pumping for Defined Scenarios**

	Volume Pumped (thousands of acre-feet)		
	No Earthquake	50 Breaches	30 Breaches (Sherman Upgraded)
<b><i>First Water Year, Year of the Earthquake (July through September)</i></b>			
CCWD	30	0	0
Banks and Tracy	1,830	0	0
<b><i>Second Water Year (October through February)</i></b>			
CCWD	40	0	0
Banks and Tracy	2,430	0	0
<b><i>Second Water Year (March through September)</i></b>			
		Begin June 15	Begin May 15
CCWD	10	50	60
Banks and Tracy	3,680	600	800
<b><i>Third Year (October through February)</i></b>			
CCWD	40	No Disruption	No Disruption
Banks and Tracy	2,430	1,600	No Disruption
<b><i>Third Year (March through September)</i></b>			
CCWD	10	No Disruption	No Disruption
Banks and Tracy	3,680	1,200	No Disruption
<b><i>Fourth Water Year (October through September) – No Disruption</i></b>			

## 5. Economic Consequences

This section describes the analysis of economic consequence associated with seismic levee failures in the Delta. The analysis was considered in two parts. The first part addresses the in-Delta costs (i.e., emergency response and repair, infrastructure costs, crop losses, etc.), and the second part concerns the economic consequences to the state due to disrupted water exports. The assessment of economic consequences considered both the costs to the state as well as the overall economic impact to the state. The economic costs measure the net loss to the state's economy. The impacts include additional items where the economic damage to one party has been counterbalanced by an economic advantage for someone else in the state. For example, farm profits that were lost due to restricted water supplies in the San Joaquin Valley might be counterbalanced by profits to other farmers in the Imperial Valley. These lost San Joaquin profits would not be "costs" but would be "impacts."

Economic data and analysis tools are not readily available to estimate the costs and impacts that result from Delta levee failures and water delivery disruption. As a result, an approach was developed to estimate both the in-Delta and the statewide economic consequences. The next subsection describes the approach and remaining subsections describe the analysis results.

### 5.1 Approach

To estimate the economic consequences associated with Delta levee failures and water delivery disruptions, an approach was developed to estimate economic consequences (costs and impacts) as a function of the number of levee breaches that occur as a result of a seismic event. To start, three types of economic consequences were recognized:

- "Costs" to the state's economy net of any transfer payments among parties,
- "Impacts"<sup>4</sup> to the state, including both "costs" and transfer payments among parties, and
- Impacts on employment in the state.

These types of consequences are alternative measures of the economic effects of Delta damages and water export disruptions.

The estimate of each type of consequence (listed above) consists of:

- In-Delta economic consequences, and
- Water export disruption economic consequences.

These consequence components are distinct and additive. Each is estimated and summed to estimate the total consequence (cost or impact).

The In-Delta consequences include emergency response and levee repair costs, as well as other economic consequences (discussed in the next subsection). The second part concerns the economic consequences that arise from disruptions of Delta water exports by the State Water Project (SWP) and the Central Valley Project (CVP).

---

<sup>4</sup> The economic impacts include the costs to the state's economy.

## 5.2 In-Delta Consequences

There are several elements to the in-Delta consequences that may result from levee failures and island flooding. These consequences include:

- breach repair costs,
- levee reinforcement costs (to protect interior levee slopes against wave action),
- island pump-out costs,
- emergency response management and logistical costs,
- island crop loss,
- flooding damage to island infrastructure and other property,
- disruption of crop irrigation on unflooded islands,
- disruption of flooded island agriculture during the repair and pump-out period.

Data to estimate these costs is not readily available and only limited effort could be allocated to modeling these costs in the present study. The most useful information that is available comes from the recent Jones Tract levee breach. As reported by Mount and Twiss (2004) to the California Bay Delta Authority Integrated Science Board Levee Subcommittee, the overall economic consequences of the Jones Tract incident were described as follows:

*"According to DWR staff, costs to the government alone for this break exceeded \$44M. This does not account for crop losses, job losses, farm infrastructure repair or carriage water releases to maintain water quality. Estimates of total costs of the Jones Tract failure reported in the Sacramento Bee and Contra Costa Times approach \$90M (quoted from California Office of Emergency Services sources) ...."*

The In-Delta consequences for the Jones Tract event do not include any significant water export disruption impacts. Such impacts have not been reported and are believed to have been negligible for the Jones Tract event.

In the absence of better information, the estimate of the Jones Tract economic consequences is used to develop an In-Delta cost model.

Some in-Delta economic consequences are directly related to the levee breach itself, e.g., the cost of breach repair. These costs are assumed to be proportional to the number of breaches. Other consequences, such as crops lost to flooding and the pump-out costs, are more reasonably proportional to the number of islands flooded.

The Jones Tract incident involved one levee breach and resulted in flooding of two islands, Upper Jones Tract and Lower Jones Tract. To estimate unit rates of consequences in terms of levee breaches and flooded islands, it is necessary to allocate the overall numbers to the breach and the two flooded islands. In this analysis, consequences of \$30 million per breach and \$30 million per flooded island were assumed. In addition, it was also necessary to distinguish between the three types of economic consequences – costs to the state economy, overall impacts including transfer payments, and jobs. For purposes of this analysis, it was assumed that all per breach consequences were costs (and were equal to

per breach impacts). Further, it was assumed that half of the per island consequences were “costs” (and “impacts”) and that the other half were additional “impacts” but not “costs.”

For purposes of this analysis, no attempt was made to estimate in-Delta consequences in term of jobs or employment.

In summary, the characterization of the in-Delta consequences based on the Jones Tract event data is:

- Overall economic “impacts” = 1 breach @ \$30m + 2 islands @ \$30m each = \$90m.
- “Costs” to the state economy = 1 breach @ \$30m + 2 islands @ 0.5 x \$30m each = \$60m.
- Employment consequences are not addressed.

Looking back at the information reported by Mount and Twiss (2004), their \$90m is comparable to our overall “impacts” and their \$44m cost to the government is included in our \$60m “costs.” The other \$16m in our \$60m “costs” includes damage/repair costs to crops, infrastructure and other private property. The \$30m that we characterize as “impacts” (but not “costs”) would include such things as transfer payments (see Appendix B for more elaboration on these concepts).

For purposes of estimating in-Delta economic consequences for other events, it is necessary to relate the number of levee breaches to the number of islands flooded in an event. For the seismic scenarios explicitly modeled in this analysis, there were two cases:

- 50 breaches (Delta As-Is), flooded 21 islands, and
- 30 breaches (Sherman Island seismically upgraded), flooded 20 islands.

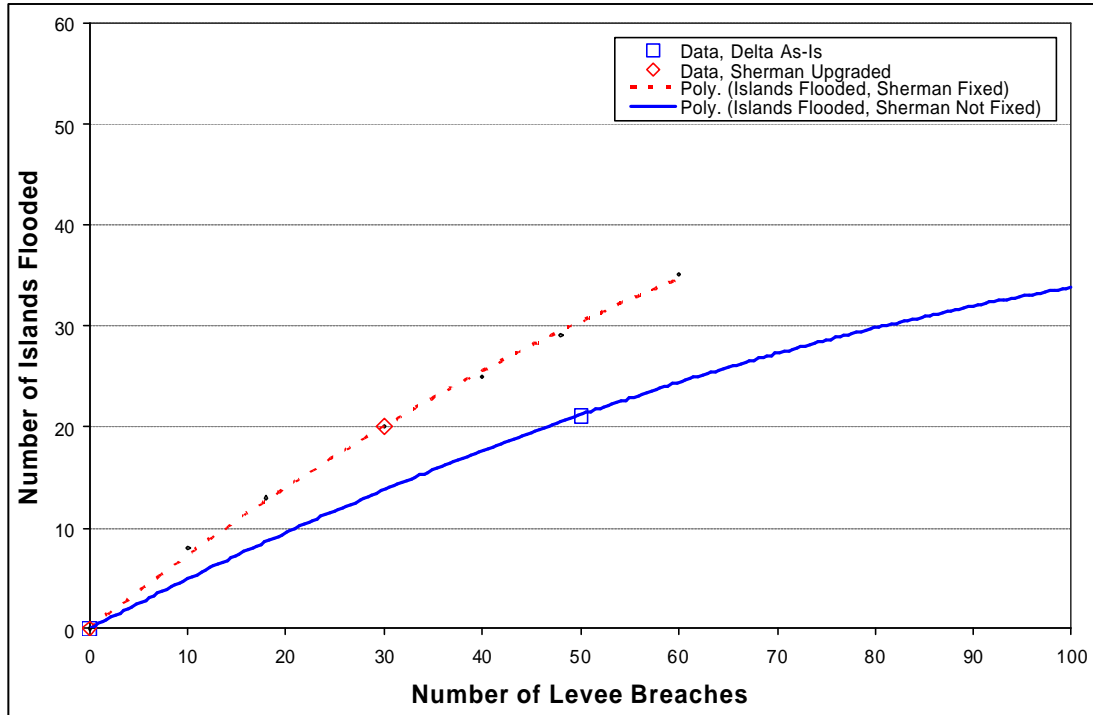
These two examples were used to define relationships between the number of breaches and the number of islands flooded. Two relationships were developed to represent the two states of the Delta considered; the Delta As-Is and the Delta with Sherman Island upgraded. These relationships are shown in Figure 5-1. These relationships were based on the two scenarios considered in this analysis, the assumption that the number of islands flooded increases at a decreasing rate as more breaches occur, and limiting conditions.

Given the relationships in Figure 5-1, relationships for the In-Delta costs and impacts and the number of breaches could be calculated. These are shown in Figure 5-2.

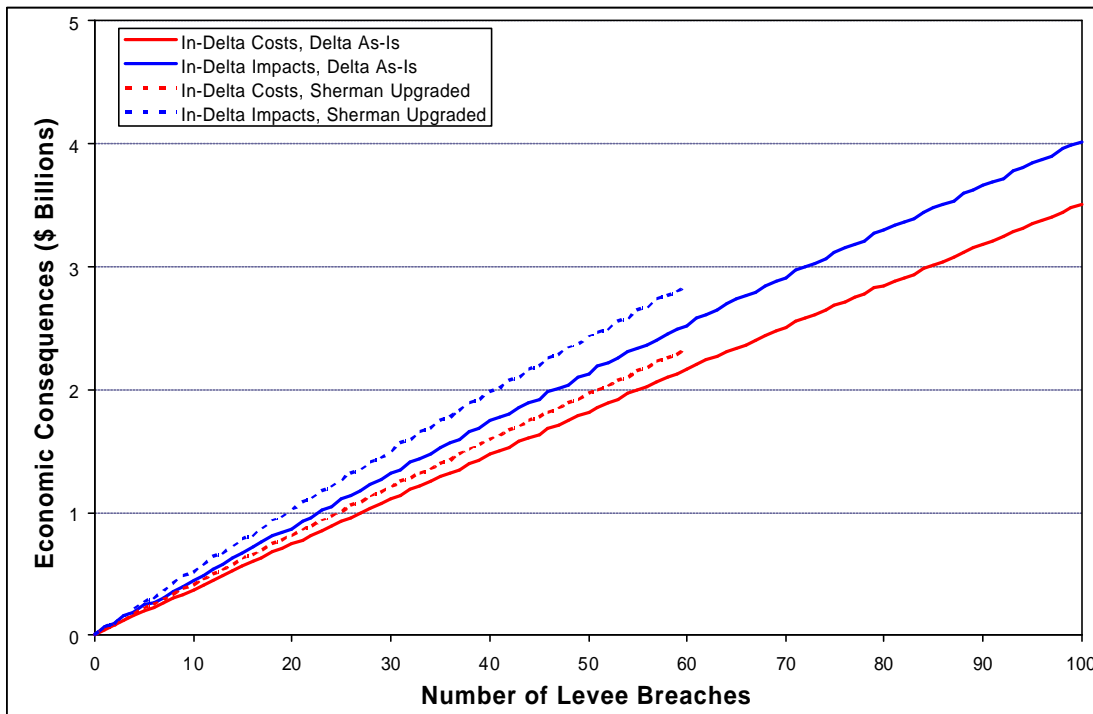
Resources available for this analysis limited the degree to which in-Delta consequences could be evaluated. The approach taken relies on the recent experience from the Upper Jones Tract levee break. Based on available information, the Jones Tract event does not provide carefully compiled information on the consequences to the Delta economy. However, the overall impact figure reported likely includes some allowance for these indirect and induced impacts.

This approach is approximate in that per island costs are based on data for Jones Tract and do not necessarily apply to other islands. Further, this model does not take into account other factors that may impact repair operations such as weather. Nonetheless, as a first approximation based on the Jones Tract experience, this model is judged to provide a realistic, useful estimate of the economic consequences.





**Figure 5- 1 Relationships between the number of breaches and the number of islands flooded in the Delta.**



**Figure 5- 2 Relationships for the In-Delta economic costs and impacts as a function of the number of levee breaches. Relationships are provided for the Delta As-Is and for Sherman upgraded.**

### 5.3 Water Supply Consequences

Unlike the Jones Tract event, which provides recent and direct cost information to estimate In-Delta economic consequences, there have been no significant events involving levee failures leading to substantial water supply disruptions and, thus, no measured consequences. In addition, economic models are not available to estimate the economic consequences of such dramatic water supply disruptions. Thus, presently available information on the economic consequences of water shortages must largely be transferred from drought and rationing information and extrapolated. That information must then be analyzed and aggregated into an overall estimate of economic consequences required in this analysis.

To conduct the economic consequence analysis, a group of economic experts was assembled. With the time and budget available, the economic work group conducted an analysis based on information provided by:

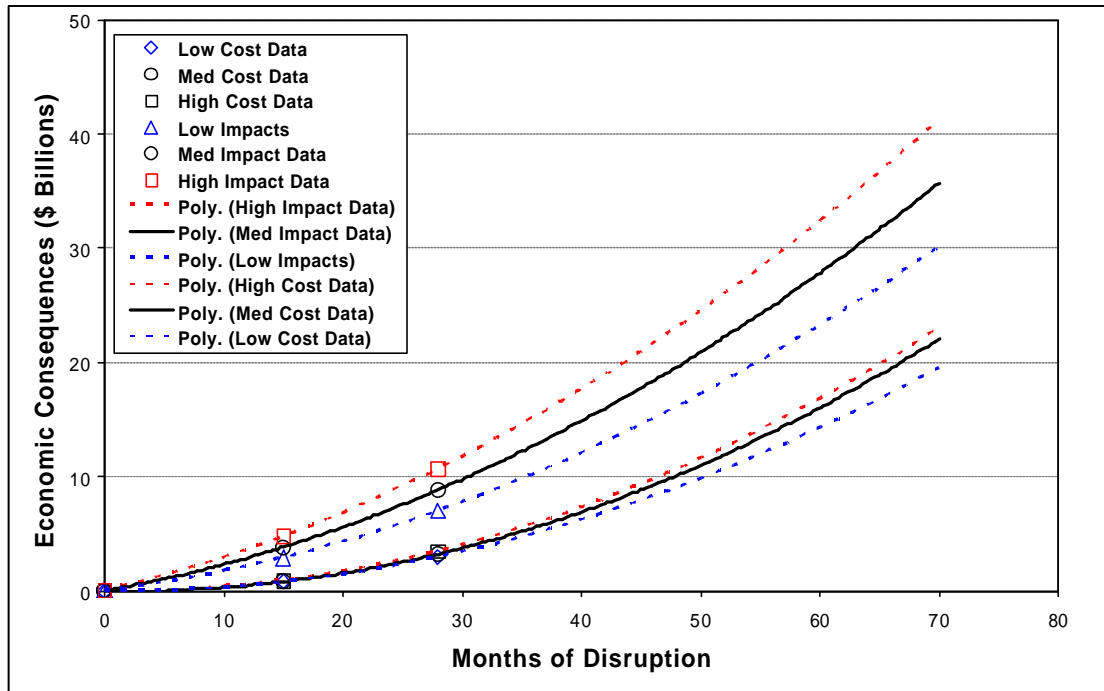
- Operations experts at the two major projects,
- Planning personnel at some of the contracting agencies,
- Individuals at other groups, including the California Division of Tourism, California Chamber of Commerce, California Farm Bureau, and individuals with experience in real estate investment and banking, and
- Drought and rationing experience.

The report of the economic work group is provided in Appendix B.

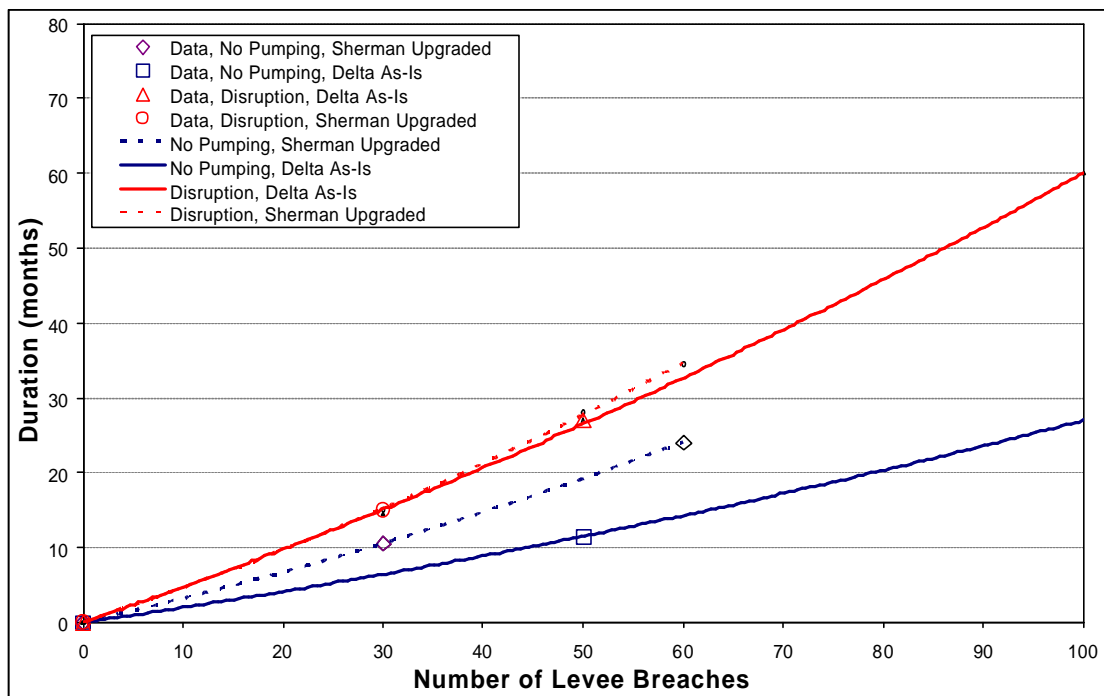
The report in Appendix B provides estimates of economic consequences from water supply disruptions for two scenarios – the 50 breach scenario for the Delta As-Is and the 30 breach scenario with Sherman Island upgraded. Note that the number of breaches and whether or not Sherman Island has been upgraded are not particularly tied to the economic consequences being estimated. Instead, the economic consequences are directly affected by the duration of the disruption and the amount of water available for delivery during the disruption period.

For the two scenarios examined by the economic work group, the duration of no pumping and the duration and amount of restricted pumping were estimated. The type of water year and the season of the year when the earthquake occurred were stipulated in the scenario definition. Thus, given a related assumption on south of Delta water storage at the time of the event, the consequence estimates by the economic work group could be (and were) based on the above inputs.

Based on the results of the economic work group, relationships between the economic consequences (costs and impacts) versus the duration of disruption were developed. These relationships are shown in Figure 5-3. The curves in Figure 5-3 are based on the results of the two scenarios evaluated by the economic work group and engineering judgment. Figure 5-3 shows a low and a high estimate in addition to the best estimate of the economic consequences. The low and high estimates are based on the range estimated by the economic work group.



**Figure 5- 3 Relationships showing the economic consequences as a function of the duration of water supply disruptions.**



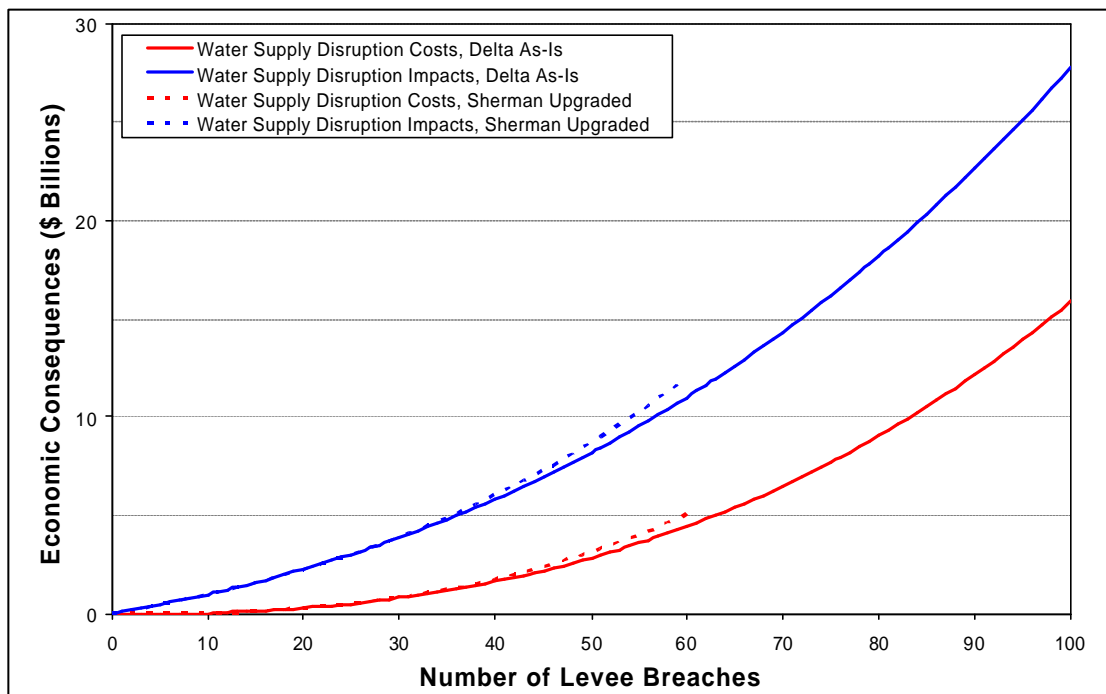
**Figure 5- 4 Relationship between the duration of water supply disruptions and the number of levee breaches. Curves are shown for the period of no pumping and disruption of pumping and for the Delta As-Is and Sherman Island upgraded.**

To apply the relationships in Figure 5-3, to other breach scenarios, relationships between the duration of water export disruption and the numbers of breaches were developed. These relationships are shown in Figure 5-4. Four curves are shown, namely:

- Duration of No Pumping, Delta As-Is
- Duration of No Pumping, Sherman Upgraded
- Duration of Pumping Disruption, Delta As-Is
- Duration of Pumping Disruption, Sherman Upgraded.

These curves are based on the information derived in the hydrodynamic and water quality studies reported in Appendix A and engineering judgment.<sup>5</sup>

Given the results in Figures 5-3 and 5-4, estimates of the economic consequences from water supply disruption can be expressed in terms of the number of levee breaches. This result is shown in Figure 5-5.



**Figure 5- 5 Relationships for water supply disruption economic consequences and the number of levee breaches. Curves are shown for the Delta As-Is and Sherman Island Upgraded and for the economic costs and impacts.**

The estimates of the consequences from disruption of water exports are considered to be biased low. They are viewed as biased low because they are based on a partial estimate of the impacts to the state. While estimates were made for various impacts within different

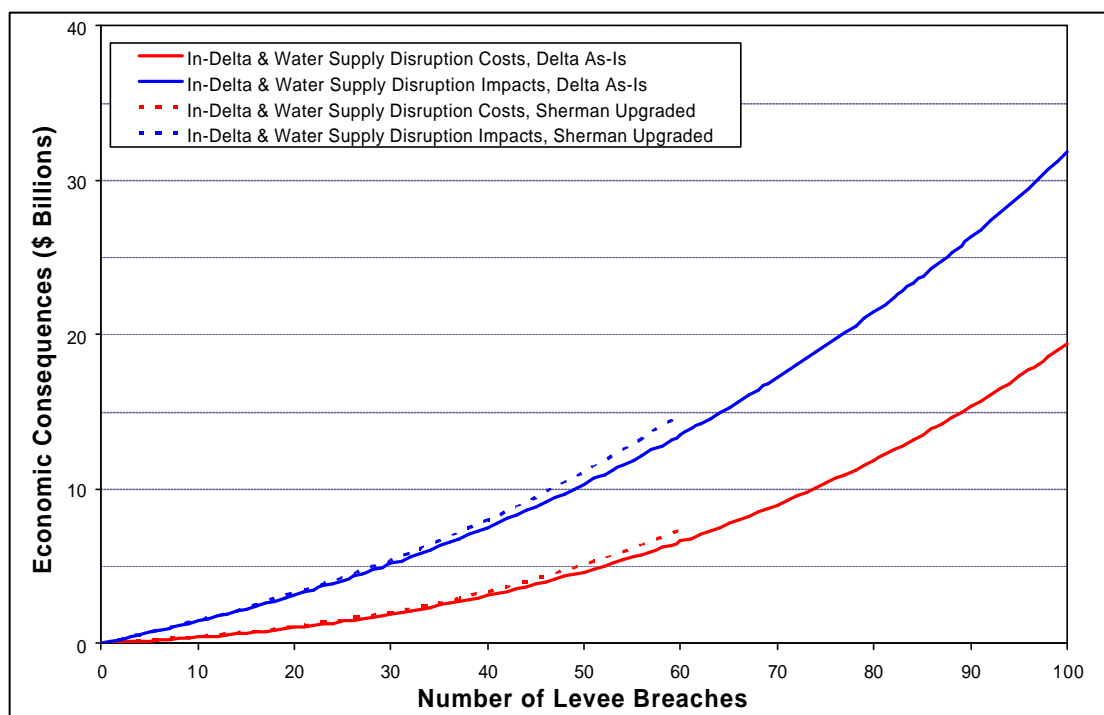
<sup>5</sup> Note, limited information was available on the duration of disruptions and on the amount of “opportunistic water” that could be pumped. Thus the duration estimates in Figure 5-4 are uncertain as is the amount of water that could be pumped. However, the economists were provided specific numbers and took them as “given”.

regions and for various groups, much of the detailed work required for estimating all the significant costs and impacts could not be performed within the scope of this project. Given the fact the consequences to all economic sectors and regions could not be evaluated, zero impacts were the de facto estimates and there is an inherent bias or under estimation.

Complicating the economic analysis is the fact that water disruption consequences were estimated only for normal water years. Consideration of dry water years seems likely to increase economic consequences. Dry years can be expected to result in large impacts that, in normal years, are negligible. For wet years, impacts might be a little less, but normal-year, negligible impacts will not be decreased significantly.

#### 5.4 Overall Economic Consequences from Seismically Initiated Levee Failures

Estimates of the total economic consequences in terms of the number of levee breaches are obtained by combining the In-Delta and water supply disruption consequences in Figures 5-2 and 5-5, respectively. This result is shown in Figure 5-6.

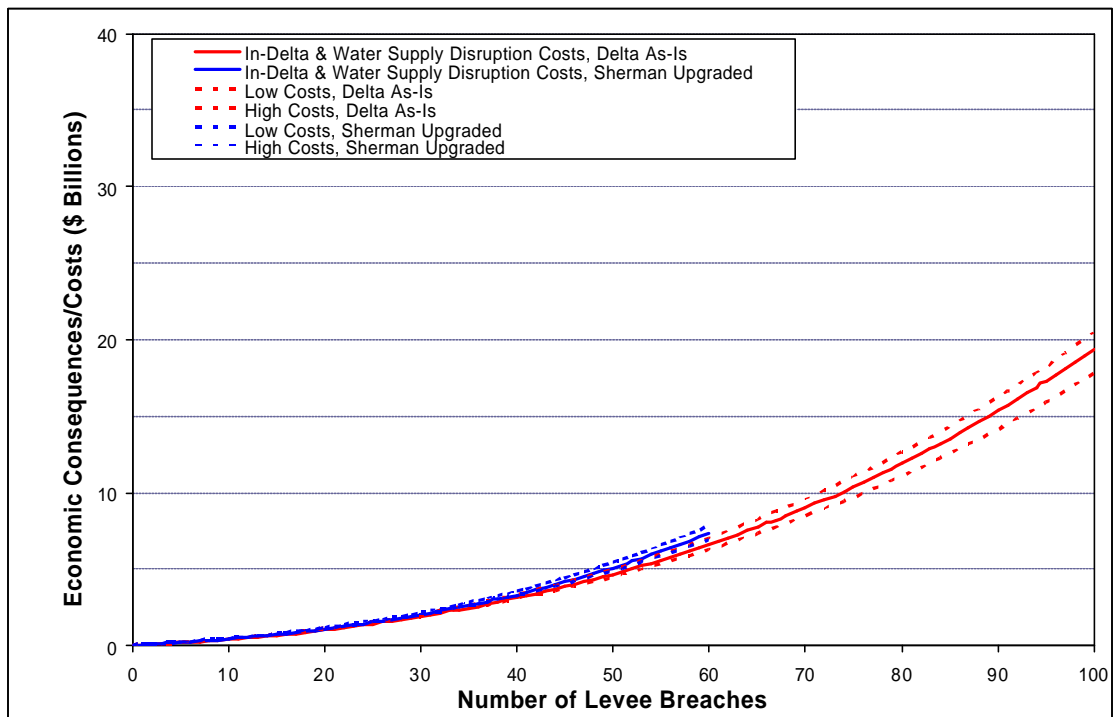


**Figure 5- 6 Total economic consequences in terms of the number of levee breaches for the Delta As-Is and Sherman Island upgraded.**

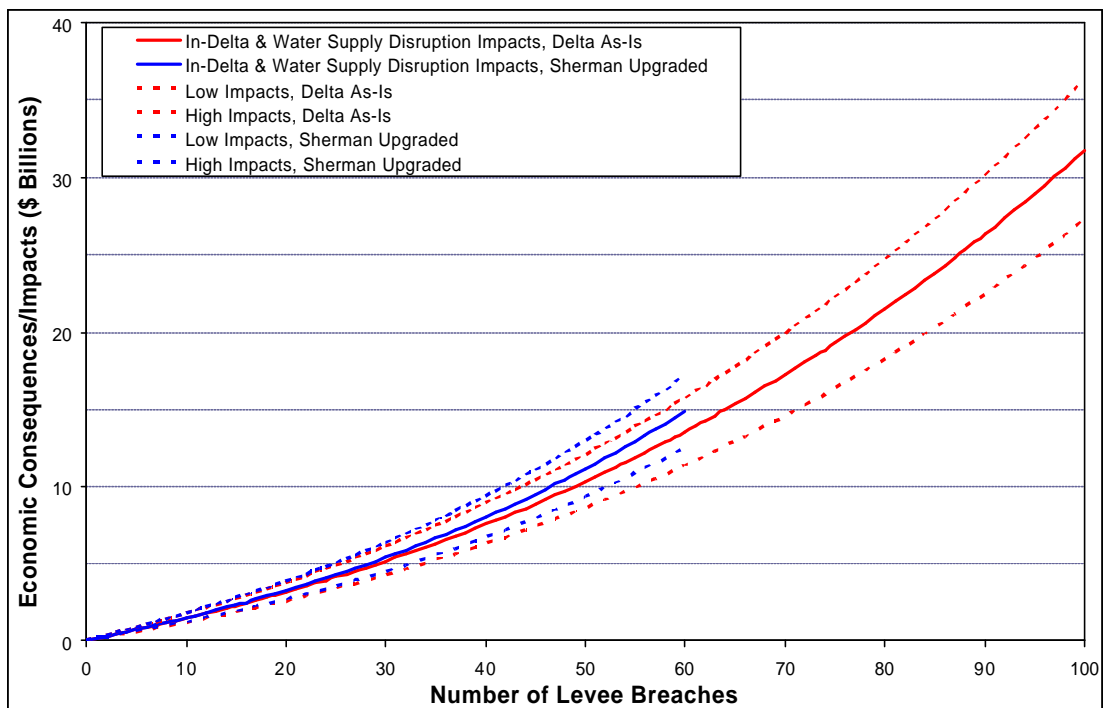
Figure 5-6 presents the overall economic consequences if the event with an indicated number of breaches occurs this year – in 2005. No attempt was made in this analysis adjust for inflation or to forecast population growth or future development conditions.

As part of their analysis, the economic work group provided a range of estimates of the economic costs and impacts for the two scenarios they addressed. However, the reader must note that other uncertainties need to be considered as well to show a more realistic picture of the overall uncertainty range. For example, there are uncertainties about the disruption durations and amounts of water that can be pumped for various breach scenarios

(i.e., given the number of levee breaches). Nonetheless, the range provided by the economists has been carried through the estimate of economic consequences (costs and impacts). The results are shown in Figure 5-7, with the low and high curves reflecting the economists' range.



(a)



(b)

**Figure 5- 7 Total economic consequences including low and high estimates in terms of the number of levee breaches for a.) costs, and b.) impacts.**

## **6. Risk Quantification and Risk-Reduction Analysis**

This section presents estimates of the seismic risk associated with Delta levee failures and risk-reduction opportunity associated with seismically upgrading Sherman Island. The seismic risk associated with levee failures in the Delta is estimated by combining the probability distribution on levee breaches (see Fig. 2-1) with estimates of the economic consequences (defined as a function of the number of levee breaches) (see Fig. 5-7). The result is a probability distribution on the economic consequences. Results are presented for both economic costs and impacts and exposure periods of 1 and 50 years.

As part of the seismic risk estimates and the evaluation of the risk-reduction potential associated with upgrading Sherman Island, the uncertainty in the estimate of the probability of levee failure (see Fig. 2-1) and the range of economic consequences are considered. This provides a qualitative measure of the uncertainty in the analysis results.<sup>6</sup>

### **6.1 Delta As-Is Seismic Risk Results**

Figure 6-1 shows the distribution for economic impacts to California as a result of Delta levee failures due to earthquakes for exposure periods of 1 and 50 years. A 50 year period is a reasonable exposure time for considering long-term policies on water project reliability and related capital expenditures.

Figure 6-2 shows the distribution for economic costs for exposure periods of 1 and 50 years for the Delta as-is.

The low and high estimates in Figures 6-1 and 6-2 were obtained by combining the 15<sup>th</sup> and 85<sup>th</sup> fractile curves for the probability distribution on levee failures (see Fig. 2-1) with the low and high estimates of the economic consequences (costs and impacts) (see Fig. 5-7), respectively. The mean estimate combines the mean probability of exceedance of levee breaches (see Fig. 2-1) and the best estimate for the economic consequences (see Fig. 5-7).

### **6.2 Seismic Risk Results for Sherman Island Upgraded**

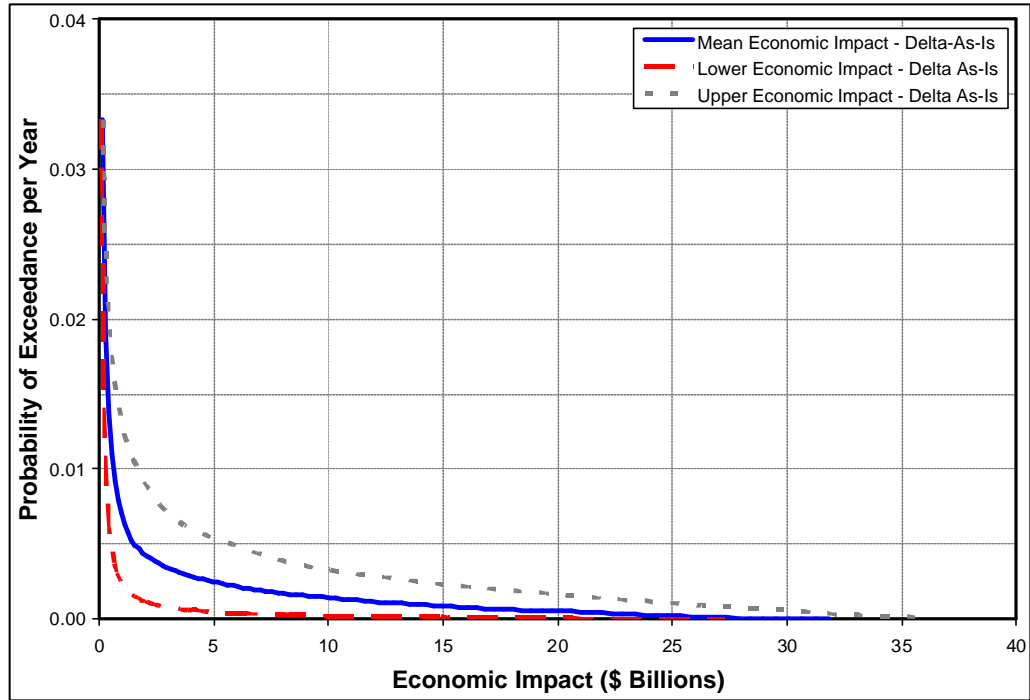
For purposes of considering the risk-reduction benefit of seismically upgrading Sherman Island levees, it is assumed the levees are upgraded to a level such that levee failure and island flooding does not occur or has a probability of occurring that is significantly lower than that of other Delta levees. In the context of this analysis, it was not possible to re-compute the seismic sub-team analysis assuming the Sherman Island levees have been upgraded. Alternatively, the seismic sub-team distribution on levee breaches was adjusted to reflect the reduced number of levee failures estimated to occur with Sherman Island upgraded.

As reported by the seismic sub-team (CALFED, 2000), the Sherman Island levees are more vulnerable to earthquake ground motions than the levees on the other islands. As a result, during a seismic event there is a relatively high probability (compared to other islands) that Sherman Island may fail. Considering a range of seismic scenarios, it was estimated that approximately 40 percent of the total number of levee failures that occur during an event,

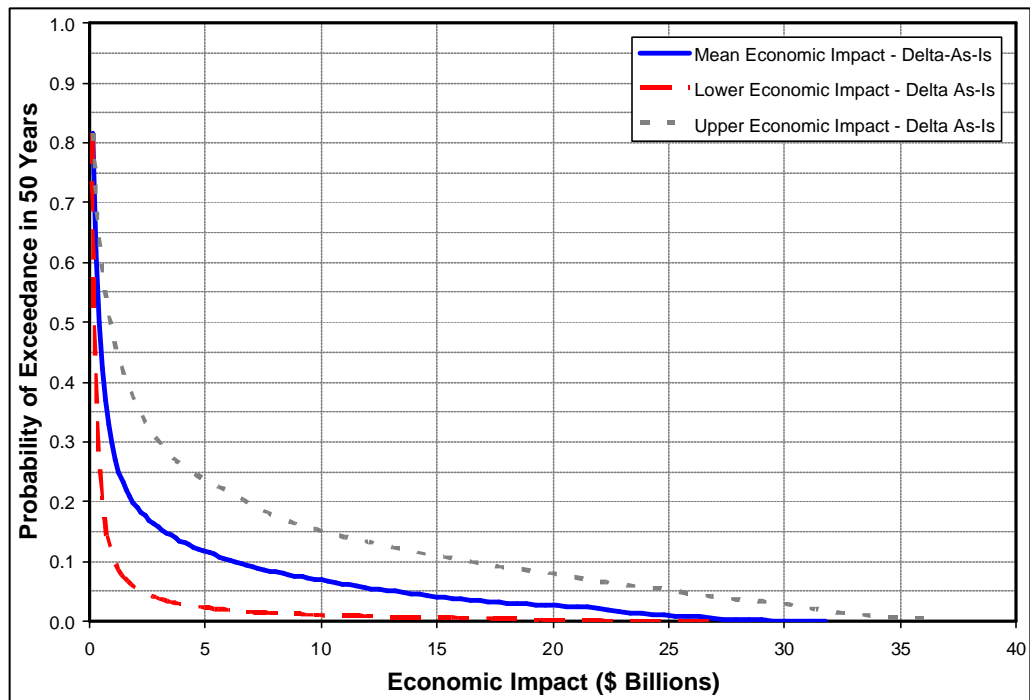
---

<sup>6</sup> The range of results presented are not the result of an uncertainty analysis, which would ordinarily be performed as part of a comprehensive risk analysis. The range provided shows the limited portion of the uncertainty information that is now available and is presented only as an illustration.



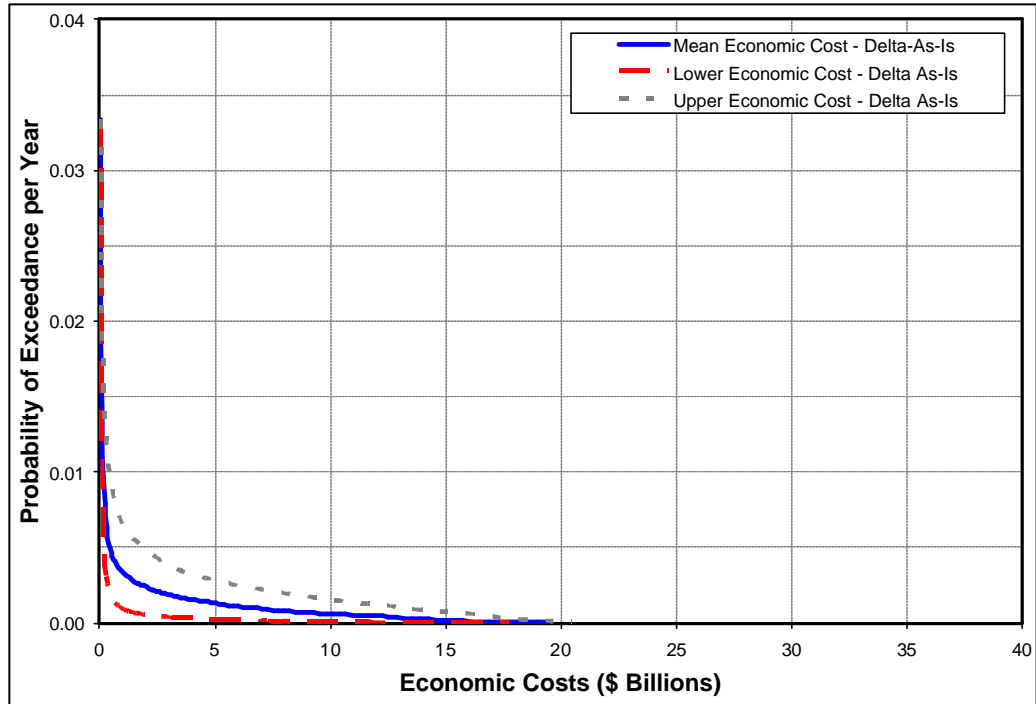


(a)

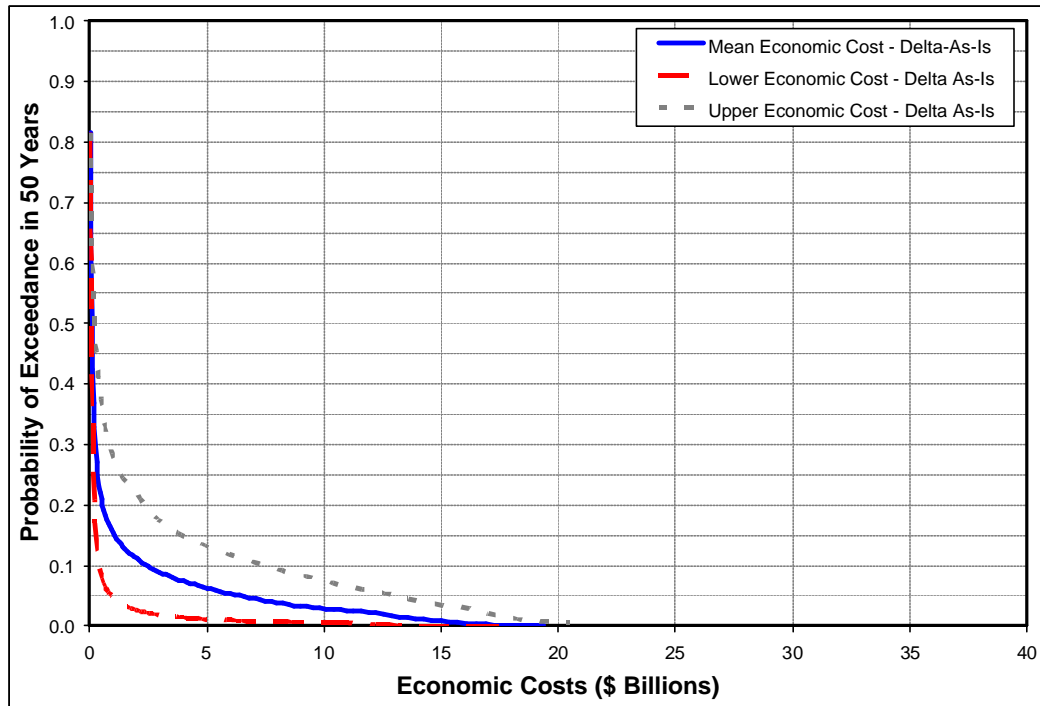


(b)

**Figure 6- 1 Probability distribution on the economic impact due to seismically initiated level failures in the Delta under as-is conditions for exposure periods of a.) one, and b.) fifty years.**



(a)



(b)

**Figure 6- 2 Probability distribution on the economic cost due to seismically initiated level failures in the Delta under as-is conditions for exposure periods of a.) one, and b.) fifty years.**

occur on Sherman Island. Based on this, an estimate of the probability distribution on the number of levee failures for Sherman Island upgraded was estimated simply by scaling the axis on the number of breaches.

Figure 6-3 shows the distribution for economic impacts to California as a result of Delta levee failures for Sherman Island upgraded for exposure periods of 1 and 50 years.

Figure 6-4 shows the distribution for economic costs for exposure periods of 1 and 50 years assuming Sherman Island is upgraded.

### 6.3 Risk-Reduction Assessment

In this sub-section the risk-reduction benefits of upgrading Sherman Island are evaluated. The benefits of an upgrade considered here are the reduced economic risks only. The reduced risks are a result of two factors. The first is the lower probability of levee failures and the second is reduction in the economic consequences. Figure 6-5 compares the estimated mean economic consequence distributions (for the Delta As-Is and for Sherman Island upgraded) for a 50-year exposure period.

To estimate the risk-reduction benefit of upgrading Sherman Island, the expected risk costs (the expected value of the economic consequences (costs and impacts)) for a 50-year exposure period are estimated. The risk costs are estimated for both cases; the Delta As-Is and the Sherman Island upgraded. The difference between these costs provides a measure of the risk-reduction benefit.

An earthquake that causes levee failures and disrupts Delta water exports may not occur for several years. To estimate the expected risk cost, the present worth of the economic consequences that could occur over the 50 year period are estimated. To determine the present worth, an annual discount rate of 5 percent was used. Table 6-1 shows the present worth of the expected risk costs for the Delta As-Is and Sherman Island upgraded. The results in the table include the low and high estimates as well as the mean.

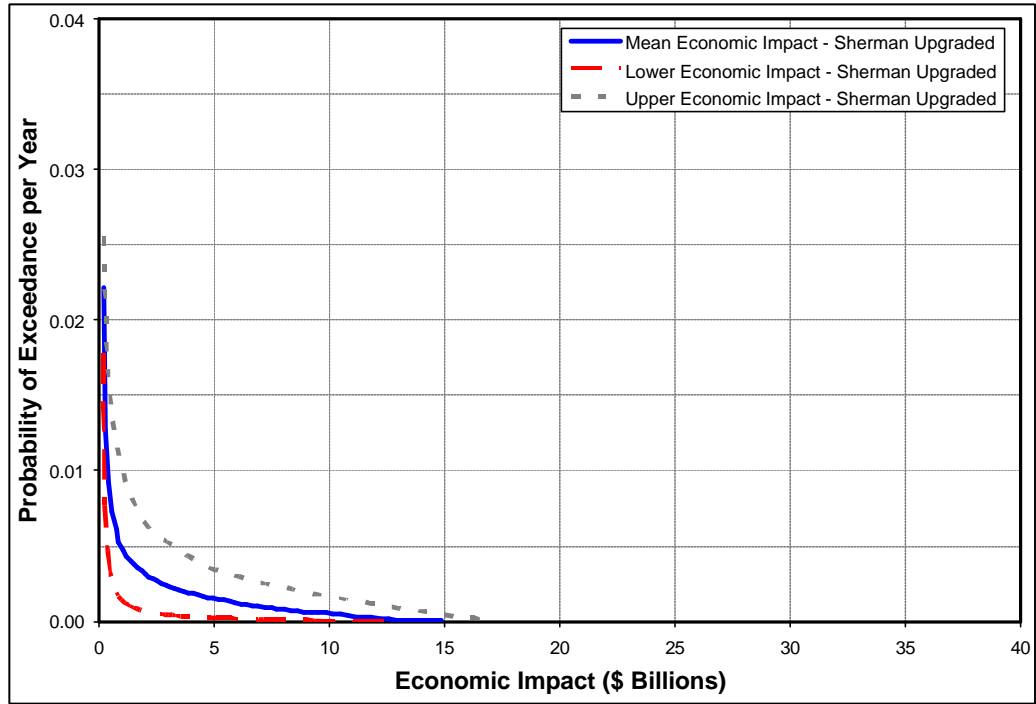
**Table 6- 1 Expected Risk Costs in Terms of Economic Costs and Impacts**

	Expected Risk Costs (\$ Millions)*					
	Costs			Impacts		
Delta Condition	Low	Mean	High	Low	Mean	High
<b>Delta As-Is</b>	120	380	820	280	890	1,900
<b>Sherman Island Upgraded</b>	50	160	350	130	450	980
<b><i>Risk-Reduction Benefit</i></b>	<i>70</i>	<i>220</i>	<i>470</i>	<i>150</i>	<i>440</i>	<i>920</i>

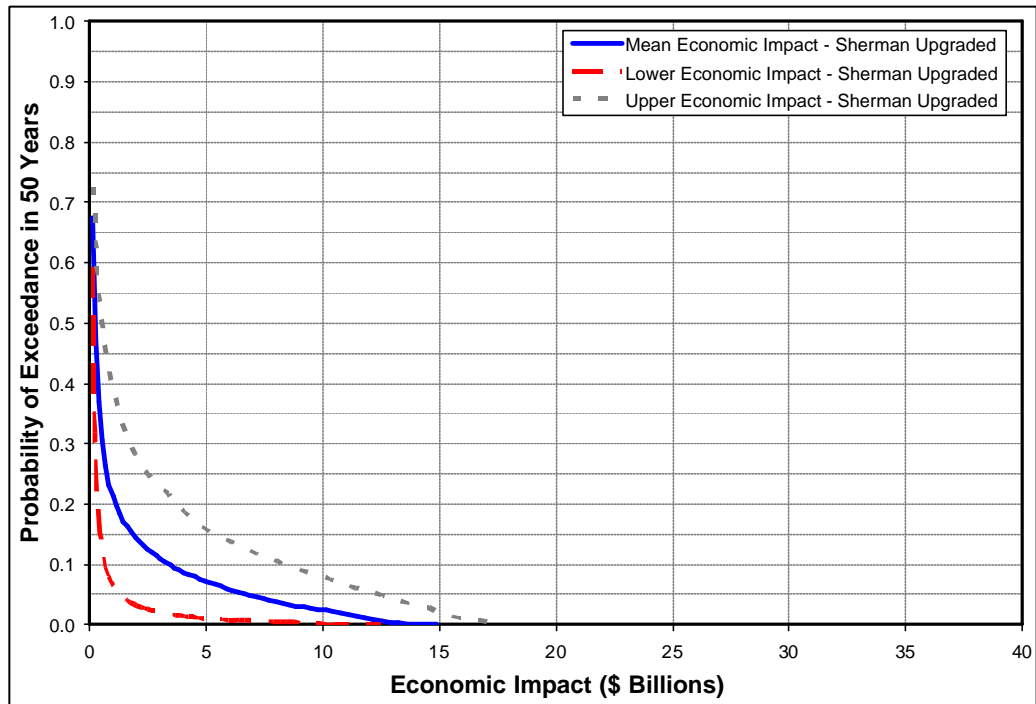
\*Results rounded

The difference between the risk costs for the Delta As-Is and with Sherman Island upgraded provides an estimate of the economic risk-reduction benefit that is expected. This result is shown in the last row in Table 6-1.

From the perspective of evaluating the economic benefit of upgrades to Sherman Island, the results in Table 6-1 indicate that an expenditure of as much as about \$220 million (based on the mean estimate of the reduction in the expected value of economic costs) may be economically justified.

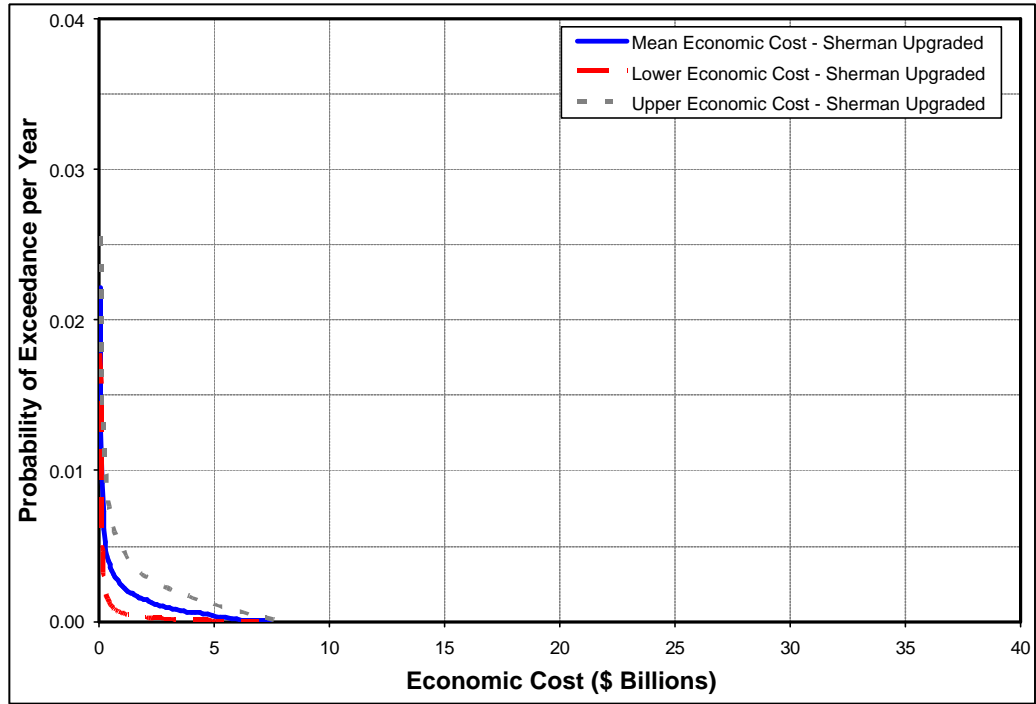


(a)

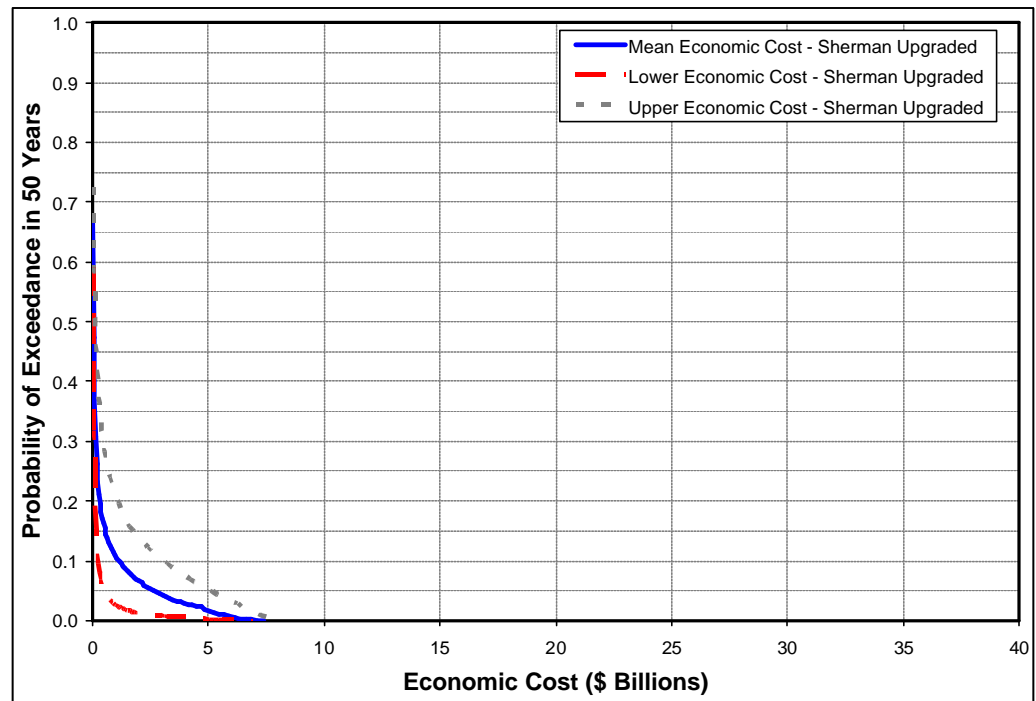


(b)

**Figure 6- 3 Probability distribution on the economic impact due to seismically initiated level failures in the Delta for Sherman Island upgraded for exposure periods of a.) one, and b.) fifty years.**

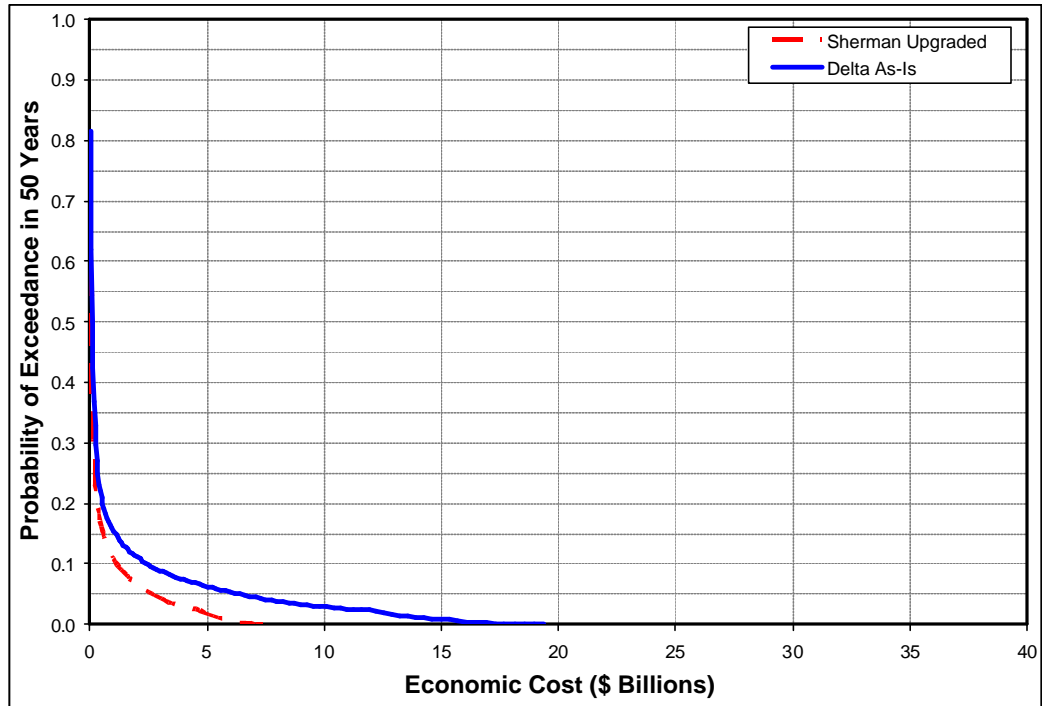


(a)

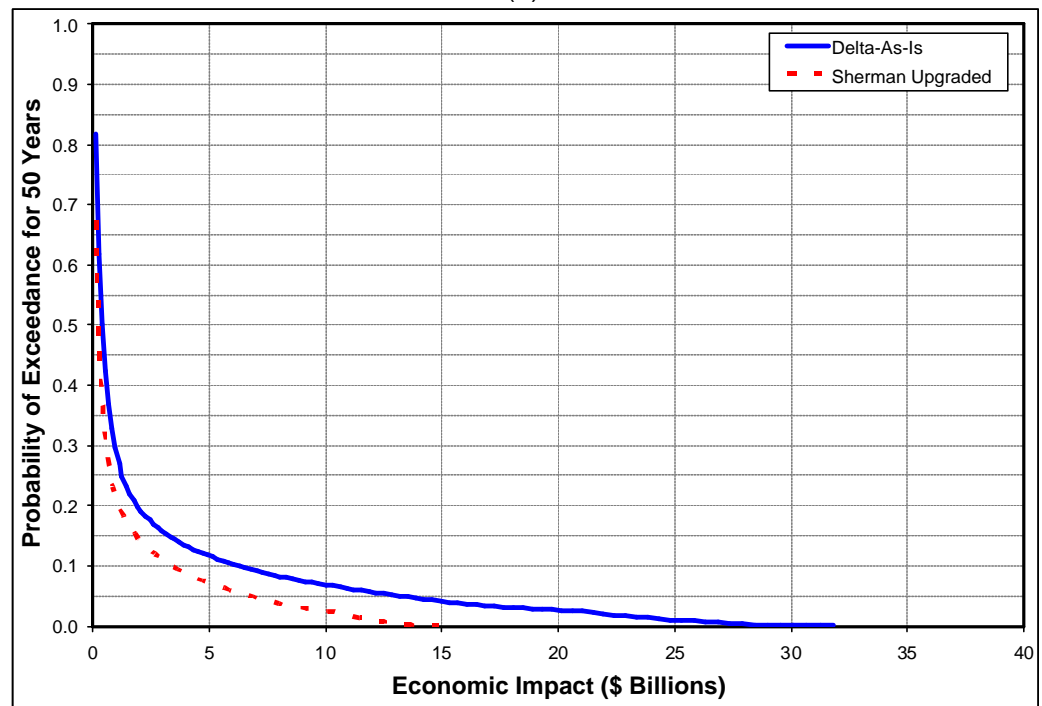


(b)

**Figure 6- 4 Probability distribution on the economic cost due to seismically initiated level failures in the Delta for Sherman Island upgraded for exposure periods of a.) one, and b.) fifty years.**



(a)



(b)

**Figure 6- 5 Comparison of the economic risk distributions for the Delta As-Is and Sherman Island upgraded for a 50 year exposure period in terms of a.) costs and b.) impacts.**

The results in Table 6-1 are necessarily approximate, given the available data and resources. Nonetheless, the comparison of the estimated risks and the potential risk-reduction benefits provide a clear sense that risk-reduction opportunities exist and they are economically justified. At the same time, this analysis did not consider whether there are more advantageous ways to achieve risk reductions comparable to those estimated here for an upgrade to Sherman Island.

## 7. Observations

This analysis provides the results of a first attempt to estimate the economic consequences and risks to California as a result of seismically initiated levee failures in the Delta. The analysis has been approximate from the perspective of analyzing the physical response of the Delta to levee failures, the impact of water supply disruptions to local and regional economies, the risk model, etc. Despite these limitations, the analysis has offered several insights that should prove valuable in conducting a comprehensive risk analysis for the Delta. Key observations include:

1. **Salinity Intrusion** – Both scenarios examined included large amounts of salinity intrusion into the flooded islands. The initial flooding volume (i.e., the “first gulp”) amounted to 1.2 million acre feet (MAF) for the 50 breach scenario and 1.1 MAF for the 30 breach scenario over the three days following the earthquake. Although the scenarios examined here considered a summer event, the flooding volumes for these severe events are large enough that substantial salinity intrusion would also occur in winter unless the earthquake occurred shortly after or during a large flood.
2. **South Delta** – Breaches and island flooding in the south Delta are much more important than initially perceived. When southerly islands flood with salinity intrusion, they trap the salt for a long period, blocking the fresh water from the export pumps. Thus, south Delta breaches should be repaired first.
3. **Pumping Disruption** – If severe earthquake damage occurs, including many Delta levee breaches (say 20, or more), a long period of water export disruption can be expected – on the order of one or two years or more.
4. **Flushing** – Using fresh water inflows to flush the salinity out of the Delta, especially in the one to two months following the earthquake, was observed to be an important part of recovery. Flushing must then continue over the full period of disruption to combat the extra tidal prism and mixing. Under the scenarios and assumptions examined, 9.8 MAF of flushing water was used in the 50 breach case and 6.5 MAF was used in the 30 breach case. These quantities might be decreased somewhat by fine tuning flow management strategies, but they would still need to be substantial.
5. **Rock Availability** – The availability of rock (meeting essential gradation and other specifications) via marine transport and placement for breach closure is a critical factor in estimating the schedule for emergency response and repair.
6. **Economic Impacts Vary Among Project Contractors** – For severe levee damage due to a summer earthquake during a “normal” water year (following and followed by other “normal” water years), the economic impacts of disrupted water export vary widely among contractors depending on their degree of dependence on the state and federal projects and availability of local storage and alternate supplies. Agricultural is likely to be heavily impacted because crops partially grown may be lost. Urban areas may experience minor or major impacts depending on their water reserves and degree of project dependence.
7. **Other Seasons** – Economic impacts may either increase or decrease if the earthquake occurs in other seasons. Agriculture would be less impacted by an earthquake occurring after harvest but before the next planting. Urban areas may be more heavily impacted by a fall or winter earthquake since their local storage may be low.



8. **Dry Years** – Inclusion of one or more dry years immediately before or within the disruption period would be expected to substantially increase economic impacts and may lengthen the disruption period due to less flushing.
9. **Impact of Disruption Period Length** – Impacts increase disproportionately with increasing length of the disruption period. Thus, the most important goal of mitigation strategies should likely be to decrease the length of relatively severe (long) disruptions.
10. **Capital Projects** – Even considering the partial and preliminary assessment conducted here, it seems clear the potential economic costs to the state from Delta seismic damage and water export disruption are of such a magnitude that substantial capital expenditures to lessen those impacts are justified, especially if they decrease the length of severe disruptions.

## 8. References

Abrahamson, N. A., and W. J. Silva, *Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes*, Seismological Research Letters, 68 (1), p. 9-23, 1997.

CALFED Bay-Delta Program, Levees and Channels Technical Team, Levees Seismic Vulnerability Sub-Team, *Seismic Vulnerability of the Sacramento – San Joaquin Delta Levees*, April 2000.

California Department of Water Resources, *After Action Report – 2004 Jones Tract Flood Incident*, December 2004.

Mount, J. and R. Twiss, *Subsidence, Sea Level Rise, Seismicity in the Sacramento-San Joaquin Delta: Report to the Levee Integrity Subcommittee of the California Bay-Delta Authority Independent Science Board*, December 2004.

Wakabayashi and Smith, 1994, *Evaluation of Recurrence Intervals, Characteristic Earthquakes, and Slip Rates Associated with Thrusting along the Coast Range – Central Valley California, Geomorphic Boundary*, Bulletin of the Seismological Society of America, Vol. 84, No. 6, pp. 1960-1970, December 1994.

Wells and K. Coppersmith, *Updated Empirical Relationships Among Magnitude, Rupture Length, Rupture Area, and Surface Displacement*, Bulletin of the Seismological Society of America, Vol. 84, pp. 974-1002, 1994